Hochschule Ostwestfalen-Lippe
University of Applied Sciences

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

Production Engineering and Management

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Production Engineering and Management

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Production Engineering and Management

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PREFACE

It is our pleasure to introduce the 8th edition of the International Conference on Production Engineering and Management (PEM), an 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. This year the conference is hosted at the university campus in Lemgo, Germany.

The main goal of the conference is to offer students, researchers and professionals in Germany, Italy and abroad, an opportunity to meet and exchange information, discuss experiences, specific practices and technical solutions for planning, design, and management of manufacturing and service systems and processes. As always, 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.

This year's special focus is on Supply Chain Design and Management in the context of Industry 4.0, which are currently major topics of discussion among experts and professionals. In fact, the features and problems of Industry 4.0 have been widely discussed in the last editions of the PEM conference, in which sustainability and efficiency also emerged as key factors. With the further study and development of Direct Digital Manufacturing technologies in connection with new Management Practices and Supply Chain Designs, the 8th edition of the PEM conference aims to offer new and interesting scientific contributions.

The conference program includes 25 speeches organized in seven sessions. Two are specifically dedicated to "Direct Digital Manufacturing in the context of Industry 4.0". The other sessions are covering areas of great interest and importance to the participants of the conference, which are related to the main focus: "Supply Chain Design and Management", "Industrial Engineering and Lean Management", "Wood Processing Technologies and Furniture Production", and "Management Practices and Methodologies". The proceedings of the conference include the articles submitted and accepted after a careful double-blind refereeing process.

Franz-Josef Villmer Elio Padoano

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DISSIMILAR METAL JOINTS – LASER BASED MANUFACTURING PROCESSES FOR COMPONENTS OF TOMORROW

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Abstract
In order to achieve the best performance for a component, it is often necessary to combine different materials. In this way, it is possible to create different sections in a component where properties are adapted to the local requirements. For example, highly loaded areas made of steel can be combined with less loaded areas made of aluminum, which leads to enormous weight savings. Due to this high lightweight construction potential, these multi-material components are particularly interesting for vehicle construction. However, thermal joining of dissimilar materials is very challenging because of their differing physical properties. In particular, the formation of hard and brittle intermetallic phases leads to cracks and an early failure of the joint. Therefore, it is the aim of many research projects to reduce the formation of intermetallic phases by limiting the mixing of the joining partners in the weld pool. For this purpose, especially laser-based manufacturing processes are suitable due to their characteristic high energy density. This actually allows the generation of usually unweldable dissimilar metal joints, which is verified by the represented research work, based on application examples in automotive, shipbuilding and solar industry.
A next step is the combination of multi-material components and powder-based additive manufacturing methods to achieve additional geometrical scope for design. This would allow the production of absolutely novel components that were previously not producible. In this context, an outlook is given how those could be realized in the near future.

Keywords:
Dissimilar metal joints, Laser processes, Multi-material components

1 INTRODUCTION

In the field of e.g. vehicle manufacturing, e-mobility, and the energy and medical sector, there is a high demand for load or function adapted components. For example, material driven lightweight construction is a preferred approach for reducing CO_2 emissions. For this, multi-material components and therefore, dissimilar material joints are needed. This means, there is also a big demand for suitable processes to join different metals. To get a solid joint between metal parts, often thermal processes are used. The challenges for these processes are differing physical properties of the material such as melting temperatures and thermal expansion. In addition, there can be an embrittlement of the joint because of a formation of intermetallic phases. In solid state, most elements have a limited solubility for each other and therefore an assimilation by these very hard and brittle intermetallic phases takes place. In combination with the typical residual welding stresses, this leads to cracks and to an early failure of the joint. For this reason, it is necessary to reduce the formation of intermetallic phases during thermal joining processes, which is possible by a mixing limitation of the joining partners in the weld pool. These metallurgical interactions become clear by considering e.g. the aluminum-copper phase diagram (see Fig. 1, intermetallic phases shown in gray).

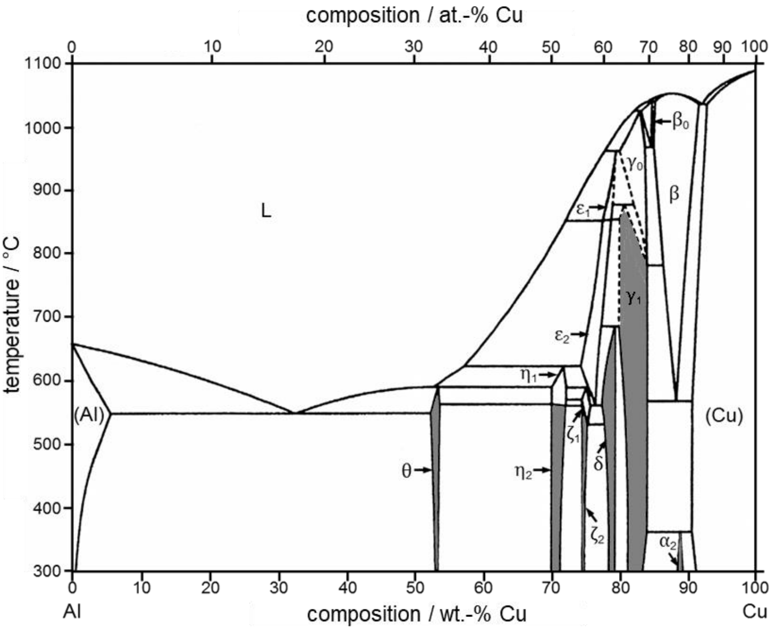


Figure 1: Aluminum-copper phase diagram, acc. [1].

2 SUITABILITY OF LASER PROCESSES FOR DISSIMILAR METAL JOINTS

The aspired limitation of the element mixing can be achieved by using laser radiation for the joining processes, because of the small beam diameter and the resulting high energy densities. The laser beam is focused by a lens on the top of the workpiece and, due to the high energy density, the metal melts and partially vaporizes (see Fig. 2, left). Based on this local limited energy input, a selective treatment of only one of the materials is possible. Therefore, the laser beam is positioned with an offset on one of the two joining partners, so that mainly this first component melts and only a small amount of the second component gets into the weld pool [2] (see Fig. 2, right). Due to the small weld pool volumes, high temperature gradients and cooling rates result, whereby the diffusion controlled phase growth is minimized [3].

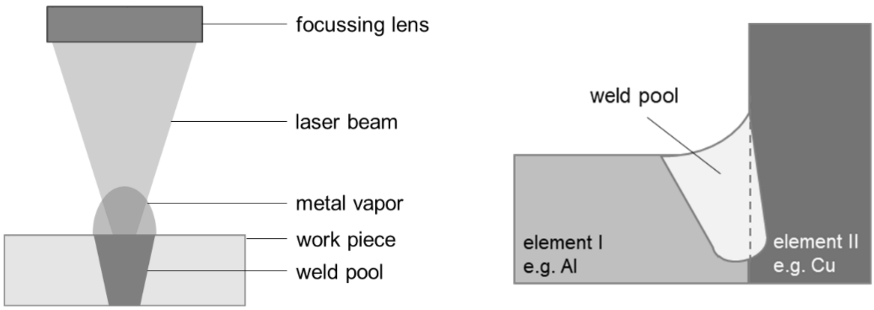


Figure 2: Schematic drawings of a laser welding process (left) and limited mixing in the weld pool (right).

3 LASER WELDING OF ALUMINUM-COPPER SOLAR ABSORBERS

A proven multi-material-component, which is already industrially fabricated by laser welding, is the aluminum-copper solar absorber. These absorbers are the central part of flat plate collectors (see Fig. 3, left), that are used to generate heat from the energy of the sun for space heating or domestic hot water. The solar absorber consists of an aluminum sheet and a copper tube. To get a thermal contact, the tube is commonly welded to the sheet on both sides of the tube by two laser sources (see Fig. 3, right).

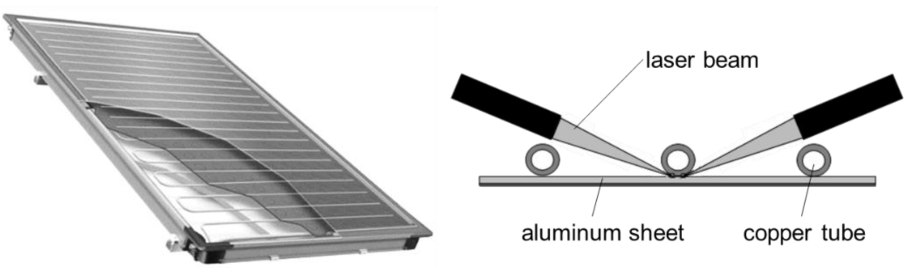


Figure 3: Flat plate collector with internal solar absorber (left) [4], schematic drawing of simultaneous welding (right) [5].

During the welding process, a huge number of spot welds with a diameter of approx. 1 mm and a spacing of approx. 2 mm is generated. Despite the mixing of the two dissimilar metals in the weld pool, only an acceptable amount of brittle intermetallic phases, due to the laser beam offset, is formed. To understand the metallurgical processes, extensive analyses of the spot welds and their characteristics are necessary. In Fig. 4 (left) a cross-section of the tube, the sheet and the two spots welds in the fillet is shown. A detailed view of a single spot weld is given in terms of a cross-section (Fig. 4, middle) and in terms of an SEM picture of an uncut spot weld (Fig. 4, right). As the laser beam is positioned onto the sheet, only the aluminum melts immediately. In addition, the aluminum partially vaporizes, so that the formed melt is pushed deep into the fillet between sheet and tube by the vapor pressure. As a result, the surface layer of the copper tube melts, which leads to a solid joint between the components with only a small amount of copper in the weld pool.

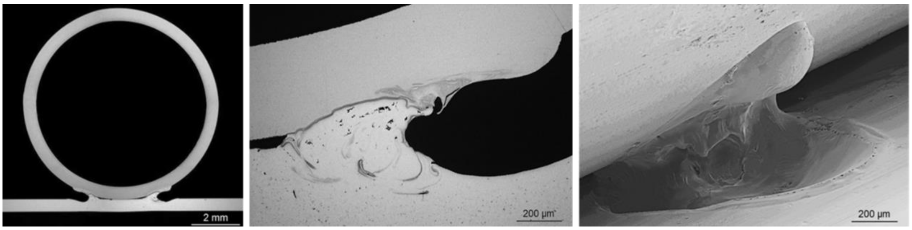
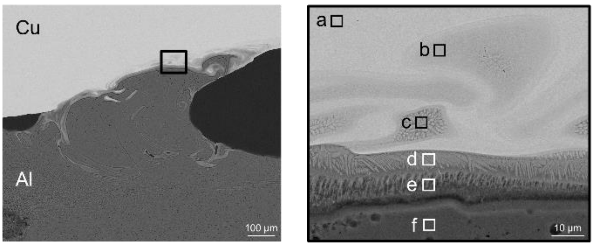


Figure 4: Characteristics of the aluminum-copper spot welds [6].

Even if a limitation of the mixing can be achieved, an intermetallic phase seam forms at the interface (see Fig. 4, middle, dark gray color). The phases within this seam can be identified by measuring their element content using SEM-detection. In Fig. 5 it can be seen, that the interface between the spot weld and the copper tube consists of several layers of different phases.



	Cu-content wt.-%	phase
a	100	Cu
b	80,32	$\delta + \gamma_1$
c	65,67	$\theta + \eta_2$
d	53,16	θ
e	27,60	(Al) + θ
f	0,75	(Al)

Figure 5: Interface and intermetallic phase seam [6].

As the dimension of the phase seam (see Fig. 5, d to e) could be limited to 20 µm by appropriate process parameters, the joints meet the given requirements concerning mechanical properties. On the basis of thermal shock tests, the operational life of solar absorbers of at least 20 years was approved.

4 JOINING OF STEEL TO ALUMINUM FOR LIGHTWEIGHT CONSTRUCTION

Another focus in the field of joining dissimilar metals is the joining of steel to aluminum for lightweight construction. The motivation for this is the approximately two-thirds lower density of aluminum compared to steel. The challenges due to the formation of brittle intermetallic phases are comparable to those in the aluminum-copper system. In the following, different application fields with customized joining approaches are presented. These are specially designed laser welding and brazing processes as well as a novel ultrasound assisted laser welding process.

4.1 Laser welding of steel to aluminum for automotive lightweight construction

In the field of material driven automotive lightweight construction, it is one aim to join an aluminum outer skin on steel structures by solid joints. Therefore, an overlap configuration with steel on top is investigated. The reason for this configuration is the higher absorption capability for laser radiation of steel, and additionally the higher solubility of aluminum in iron. Similar to welding of aluminum to copper, it is necessary to limit the mixing of elements in the weld pool to reduce the formation of intermetallic phases. For the given overlap configuration with a steel sheet on top of an aluminum sheet, this means a limitation of the penetration depth into the aluminum [7]. In the diagram in Fig. 6, a linear dependence of the penetration depth on the laser power can be recognized. This becomes even clearer by considering the corresponding cross-sections in Fig 7.

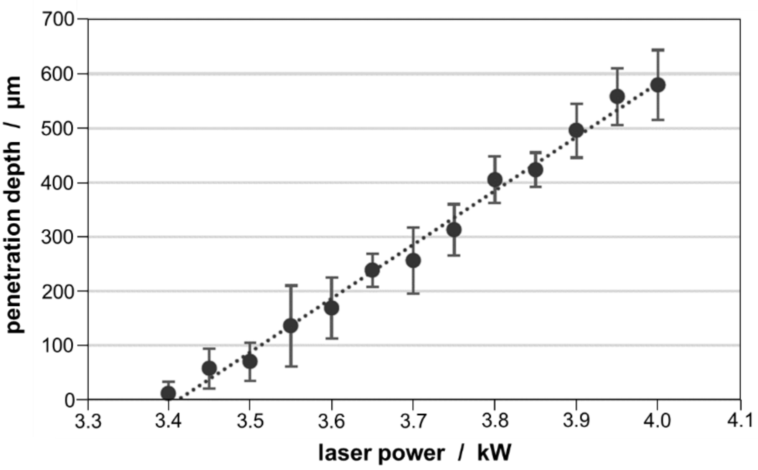


Figure 6: Dependency of penetration depth on laser power [8].

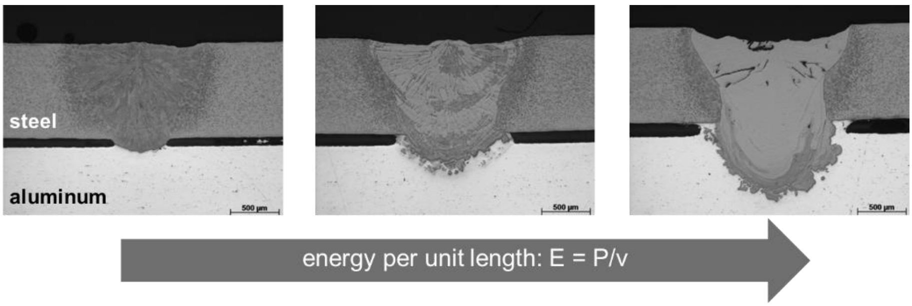


Figure 7: Cross-sections of steel-aluminum joints [9].

From the left to the right cross-section in Fig. 7 the energy per unit length (laser power divided by feed rate) increases and, as a result, the penetration depth and the joint width as well. This leads to an increase of the mixing ratio and therefore a higher amount of intermetallic phases in the weld seam. The influence of these intermetallic phases on the joint properties can be evaluated by investigating the joint strength. Therefore, tensile tests for different energy input were carried out, and the measured corresponding maximum shear forces are shown in the diagram in Fig. 8.

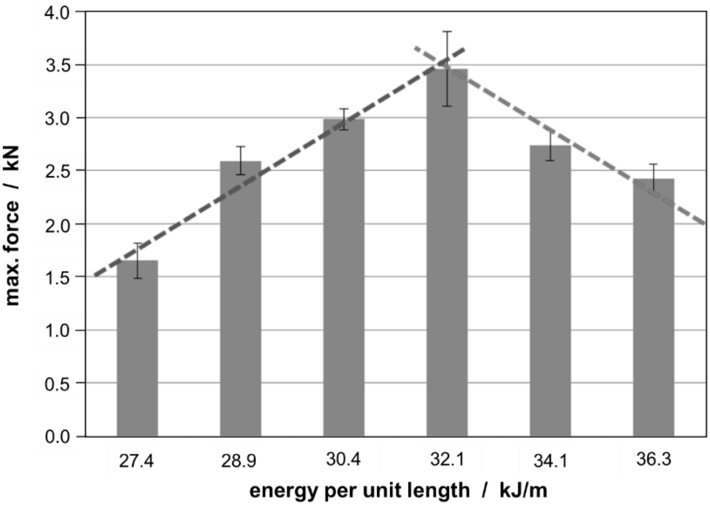


Figure 8: Strength of steel-aluminum dissimilar joints [10].

On the one hand, an increase of the energy leads to higher maximum shear forces, due to the increased joint width. On the other hand, this leads to an increased formation of intermetallic phases. Therefore, an optimum of the joint strength in dependence on the energy per unit length can be found. In this case, the joint strength is approx. 3.5 kN for a seam length of 22.5 mm, which correlates with an optimal penetration depth of 300-400 µm into the aluminum sheet. Due to this limited working range, the penetration depth should be as constant as possible, which can be reached using a laser power control [11].

4.2 Laser brazing of steel to aluminum for automotive lightweight construction

Besides laser welding, laser brazing is a suitable method for joining steel and aluminum. In contrast to the welding process, the base materials are not fused, as only the filler material melts and enables the connection between the joining partners. The solid joint results from diffusion processes within the interfaces. Advantages compared to welding processes are reduced thermal effects by lower process temperatures and a reduced mixing of the metals. Hereby, the formation of intermetallic phases can be limited more effectively to improve the formability of the joint. Disadvantages are the need for filler material, lower joining speeds and limited strength due to the filler material, which has a much lower strength than the base materials. In Fig. 9 a cross-section of a brazing joint of a steel and an aluminum sheet in a butt joint configuration is shown. The detailed view (see SEM picture in Fig. 9, right) allows identifying the intermetallic phase seam at the interface. The width of the seam is in a range of 1-2 µm, whereby the brittleness of the joint is explicitly reduced compared to a welding process. This enables even a subsequent forming of the joint [12], which is not yet possible for welded parts.

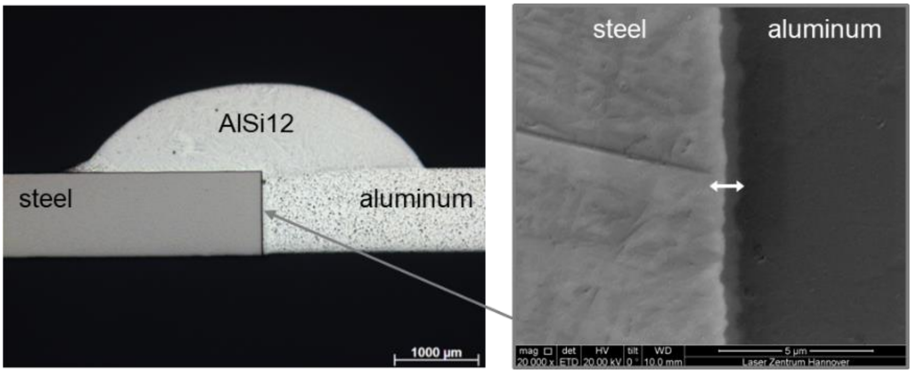


Figure 9: Phase seam of a laser brazed steel-aluminum joint [12].

4.3 Laser welding of steel to aluminum for maritime applications

Besides the automotive industry, lightweight construction is of special interest for maritime applications [13]. Especially in the field of yachts, different materials are used for body and superstructures. The upper part (superstructures) of the ship is made of aluminum components and the lower part (body) is made of steel. The challenge of joining this material combination is again the interface. Until now, explosion welded adapters are used for this application, because of intermetallic free interfaces [14]. One of the disadvantages of this method is the low scope for design regarding the adapter shape. In contrast, laser-based processes are explicit more flexible, so that there is a need for a development of a suitable laser welding process. In fundamental studies it could be already shown, that laser welding of steel to aluminum is even possible for those thick materials of maritime applications [15]. Despite required welding depths of 6 to 7.5 mm (see Fig. 10, right), high welding speeds of more than one meter per minute were reached. Based on these studies, a high power laser welding process is developed in order to generate these thick sheet steel-aluminum dissimilar joints and to replace the explosion-welded adapters. A corresponding laser welded adapter is shown schematically in Fig 10 (left). It consists of two steel cover sheets, which connect the aluminum and the steel component. In the circled region, two times three dissimilar metal joints have been realized. The tensile force of this adapter is more than 40 kN, which significantly exceeds the yield strength of the aluminum (EN AW-5083).

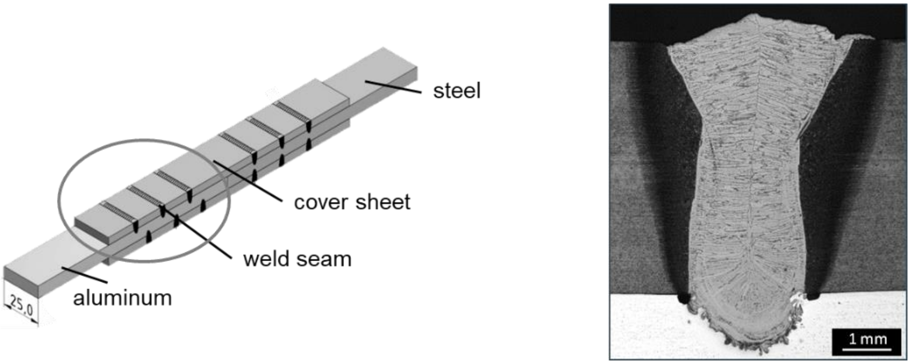


Figure 10: Laser welded adapter: schematic drawing (left), cross-section (right) [16].

4.4 Ultrasound assisted laser welding of dissimilar metal joints

A novel approach in the field of thermal joining of dissimilar metal joints represents the ultrasound-assisted laser welding [17]. In these fundamental studies, an ultrasound excitation of the molten bath is investigated. The goal of this weld pool manipulation is to reduce the amount of intermetallic phases at the interface of the weld seam significantly. The influence of this weld pool manipulation on the formation of the intermetallic phase seam is shown in Fig. 11.

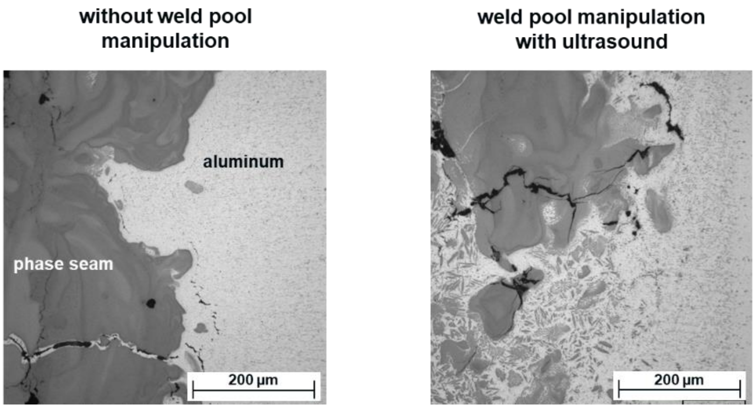


Figure 11: Influence of weld pool manipulation on phase seam [17].

It can be seen, that ultrasound excitation has a significant influence on the formation of the phase seam. The intermetallic phases are partially dispersed in the treated area, whereby the brittleness of the joint decreases. This means, that there is a high potential for increasing the formability of laser welded dissimilar joints by using this technique, which is currently investigated in further research work.

5 POTENTIAL OF MULTI-MATERIAL COMPONENTS MADE OF DIFFERENT POWDERS

In addition to the joining of dissimilar metals, the direct manufacturing of multi-material components is of special interest. Here, the components are generated using at least two different powder materials, to realize locally adapted properties while retaining the typical geometrical scope for design. By this, absolutely novel components are adaptable to given requirements in terms of material properties and geometry. Examples of schematic multi-material components made of two different powders (light and dark gray) are shown in Fig. 12.

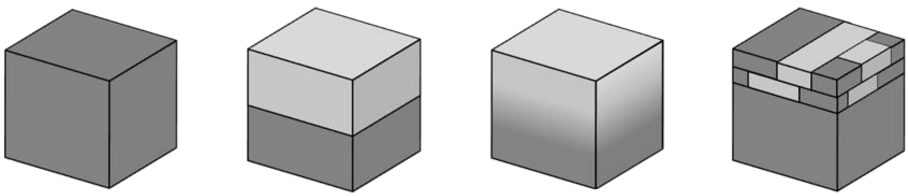


Figure 12: Schematic drawing of multi-material components made of two different powders.

In this context, many challenges have to be solved. Besides the formation of intermetallic phases and different thermal properties, the local deposition of different powder materials in one layer has to be developed. In this novel field of research, several approaches, using selective laser melting (SLM), exist and have to be investigated. Especially the design of the interface (see Fig. 13) is a suitable parameter to work on. For similar, compatible materials, a sharp as well as a graded transition can be used to reach an appropriate material change. The sharp transition only needs two separate powder stocks, whereas the graded transition requires an additional powder mixing device. For dissimilar material joints, an additional mechanical clamping should be included, to realize a suitable connection.

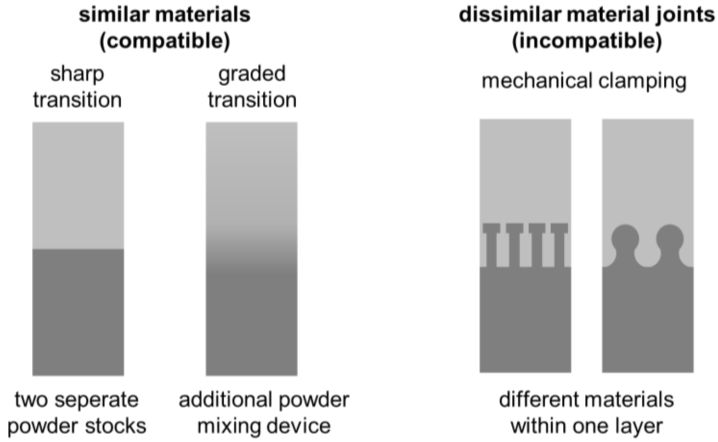


Figure 13: Design of the interface, acc. [18].

The special challenge in this case (see Fig. 13, right), is the deposition of different materials within one layer. That is not possible using conventional SLM processes so that it is an approach to upgrade the powder bed method by a selective powder deposition [19], see Fig. 14. In a first step, one powder is deposited selectively by a nozzle. Afterward, this powder is melted by laser radiation and solidifies immediately. In a third step, the second powder is deposited by a wiper, to fill up the whole layer. Finally, a selective laser melting process completes the corresponding layer of the component.

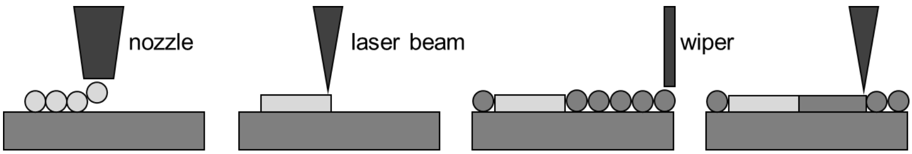


Figure 14: Process steps of a combination of powder bed and selective powder deposition, acc. [19].

6 SUMMARY

As there is a high demand for multi-material components, due to continuous product and process improvement, the joining of dissimilar metals is indispensable. Conventional processes are often not suitable, due to the huge heat input and thereby caused formation of brittle intermetallic phases. In contrast, laser-based processes are qualified due to selective and controllable heat input. Developing appropriate joining processes for dissimilar metals (e.g. aluminum and copper or aluminum and steel) makes it possible to generate multi-material components. Furthermore, additive manufacturing of multi-material parts offers the possibility to generate absolutely novel components by material combination and geometrical scope for design. For this, first developments for machine concepts started and material interactions have to be investigated systematically.

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PROCESS CONTROL FOR SELECTIVE LASER MELTING – OPPORTUNITIES AND LIMITATIONS

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Abstract
Additive Manufacturing (AM) technologies are increasingly used for final part production. Especially technologies for processing of metal, like Selective Laser Melting (SLM), are focused in this area. The shift from prototyping towards final part production results in enhanced requirements for repeatability and predictability of the part quality.
Machine manufacturers offer process monitoring solutions for different aspects of the production process, like the powder bed surface, the melt pool, and the laser energy. Nevertheless, the significance of these systems is not fully proven and threshold values for the monitored process parameters have to be determined for each product individually. This impedes the development of suitable process control systems.
The paper gives an overview of existing research approaches and available process monitoring systems for SLM and their applicability for predicting certain part characteristics. The existing solutions are evaluated based on own research results. Next, AM specific difficulties for the development of process control tools and possible solutions are discussed.

Keywords:
Additive manufacturing, Process capability, Process monitoring, Quality assurance, Final part production

1 INTRODUCTION

Companies are increasingly trying to apply additive manufacturing (AM) for the production of final parts, as it has the potential to solve certain problems in the context of decreasing lot sizes and product individualization [1]. To exploit the potential of the technology, AM has to be integrated into the product realization process. This has to start in the design phase, by respecting process specific requirements as well as using new degrees of freedom of design. In addition, changes in the production process itself are necessary: AM machines have to be integrated into industrial process chains. This requires an increased level of automation as well as the development of consistent data models. [2] Furthermore, the process quality of AM processes has to be improved to allow the production of a reliable part quality. A first step has to be the determination of the current status. Most quality management techniques to evaluate the process quality are not directly applicable to AM, as they are based on statistical methods [3] and process specific characteristics need to be respected. This makes it currently necessary, to qualify the AM process for each product individually, which causes a high effort and impedes the industrial production of individual parts. The identification of suited control parameters and the development of process control systems can contribute to solving this issue.

2 SELECTIVE LASER MELTING

Selective Laser Melting (SLM) is a powder bed fusion technology for metal materials. In the process, a layer of powder is spread on a build platform and then the powder is selectively fused where the part is to be generated. A laser beam delivers the energy for the melting. Next, the platform is lowered by one layer thickness, a new layer is spread and fused again. This procedure is repeated until the full height of the product is reached. Thus, the final product is generated layer by layer and surrounded by the residual powder.

The fusion is based on a liquid phase sintering as the laser beam completely melts the powder. In this way, almost completely dense products can be produced. SLM has a great potential for application in final part production due to the achievable mechanical properties and the large choice of materials. Nevertheless, some restrictions of the process have to be considered. On the one hand, the surface quality and dimensional accuracy are relatively low, compared to established subtractive processes. This can be improved only to a certain degree, due to physical conditions. Thus, functional surfaces or areas with very small dimensional tolerances often need an additional subtractive processing. On the other hand, all additive manufacturing technologies suffer from very limited commonly available process knowledge. This leads to a lack of suitable quality management methods and uncertain repeatability or process capability and consequently hinders the widespread acceptance of AM in the industry. [1]

A large number of process parameters influences the SLM process. Besides those of the in-process, also many factors of the pre- and post-process stages have a strong impact on the process result. For the build process itself, a large number of parameters need to be defined. They include the definition of the exposure strategy, e.g. hatch definition, laser energy, and scan speed, as well as the environmental control of the build chamber, including gas flow, atmosphere, and temperature. The extensive number of influencing parameters aggravates the development of suitable methods for process control and quality assurance, especially as the quantitative correlation between the parameters and the process results are mostly unknown. [4]

3 PROCESS MONITORING

The implementation of process monitoring systems in SLM can help to overcome the problem of limited or unproven repeatability of the build process. In a first stage, it can enable the identification of defects during the build process, and in the future, may lead to the development of closed-loop control systems. However, to achieve this, it is necessary to determine, which parameters need to be monitored and to define threshold values for these parameters. In the context of applying AM for final part production, the topic of process quality and process control is gaining more and more interest in the research community. Besides this research focus, many machine manufacturers offer different solutions for process monitoring, especially in the area of metal AM. The high relevance of this topic is also reflected by the fact that in 2016 a manufacturer of SLM machines won the International Additive Manufacturing Award for a new process monitoring system [5]. This chapter gives an overview of the state of the research and existing commercial solutions for process monitoring in SLM.

3.1 Research approaches

Three main areas of research activities can be identified in the context of process monitoring: the influence of process parameters on the part quality, development and validation of process monitoring systems, and simulation of the SLM process and resulting part characteristics.

Influence of process parameters

Many researchers address the topic of influencing factors on part quality in SLM. The results of these studies are difficult to compare as completely different approaches exist. Nevertheless, it is essential for the development of process monitoring and process control to know the most important influencing factors and their interrelations.

A huge amount of process parameters can be identified, regarding the feedstock, the build environment, the laser, and the melt pool. The parameters can either be predefined or influenced by the individual parameter settings. For all these parameters it is also listed, whether they are monitored by the applied machine or not. Taking all this into account, it can be concluded, that still a number of relevant parameters, e.g. the melt pool temperature, stay undefined and should be monitored during the build process. [6]

Other research work is focused on the influence of a limited number of parameters on selected part properties. Many of them focusing on the influence of the energy density or energy input into the powder bed and its influence on microstructure and porosity.

One example for this is the evaluation of the influence of the volumetric energy density on microstructure, porosity, hardness, surface roughness, and chemical composition of SLM parts made from stainless steel. In this experiment, the process parameters point distance and exposure time are varied to achieve different values for the energy density. The results show an

influence of the energy density on porosity and hardness and also a correlation between hardness and part porosity. The point distance is found to affect the surface roughness. [7]
Further research work also addresses the influence of energy density on porosity and microstructure of stainless steel but uses a different approach for the parameter settings. Besides achieving different energy densities through variation of the scan speed, a second test is set up with constant energy density but varying combinations of laser power and scan speed. Here, in both tests certain combinations of parameters are found, that result in an increasing porosity. Furthermore, the changing parameter combinations lead to a change in the grain size of the microstructure. [8]
Certain differences between the research approaches are due to different concepts of the machine control, especially whether the speed of the laser movement is defined by the scan speed or by a combination of point distance and exposure time at each point. Despite certain differences in the experimental setup, both detect an influence of the energy density. This is supported by the investigation of process parameter influences on geometrical properties of single melt tracks. Here the strongest influence is detected for laser power and weaker ones for layer thickness and scan speed. [9]
In contrast, it is shown in other experiments, that at constant energy density the scan speed is significant for the porosity of SLM parts build from an Aluminum alloy [10].
Other research work focuses on parameters, that cannot be influenced during the build process and thus are of limited interest in the context of process control. One example is the effect of the positioning and orientation inside the build chamber on surface quality and porosity [11], which has to be considered during the data preparation. Another one is the influence of the shield gas flow profile on the part density. This is defined by the machine design. [12]

Process Monitoring
Different approaches towards process monitoring of SLM can be found in the literature. Most of them are based on optical measurement methods, but a variety of measurands is used. One option is the monitoring of the melt pool, which is done by either camera- or photodiode-based systems.
It is shown that a camera-based system detects changes in the measured signals of the melt pool emission in areas, where the final part shows failures. The researchers also point out, that very high frame rates are required to get a sufficient resolution of the melt pool due to the fast scan speed of the laser beam. [13]
Another approach is the use of photodiodes. A general setup is presented for measuring the melt pool emission with a photodiode and position-dependent assignment of the measured values, thus describing the basics of photodiode-based measurements without any evaluation of the applicability of the measured values for the process monitoring of SLM. Additionally, in this approach, a camera is applied to monitor the powder application in the

individual layers. It is stated that only a combination of melt pool and powder bed monitoring is sufficient to predict the part quality. [14]
Another method also uses a photodiode-based system to detect a lack of fusion in the build process. Two photodiodes are utilized for measuring the emitted light from the melt pool. Like for the camera-based approach, it can be shown, that signals vary in areas with failures in the produced part. [15]
Besides the monitoring of the powder surface and the melt pool, which aims at the identification of pores and failures in the microstructure, other research addresses the geometrical characteristics of the parts produced. One approach is the use of three-dimensional images to evaluate the contour data and the surface topography of each individual layer. This system enables the detection of errors in the powder application, like a lack of powder, damages of the coater or holes in the powder bed. As a result of the image processing, the real contour data of each layer can be compared to the sliced model. [16]
Single approaches can be found that use non-optical measurement methods, like the ultrasonic process monitoring. Here, an ultrasonic transducer is mounted under the build platform and a measurement is done after each finished layer. A general applicability to detect larger voids can be shown. [17]

Simulation of the SLM process

A multitude of simulation models can be found for different AM processes. Especially in the area of SLM, most approaches intend to explore the physics behind the process more in detail [18].
The modeling approaches for metal AM can be grouped into four categories: Process, Microstructure, Properties, and Performance. The different categories are interrelated and a need for process modeling and simulation approaches that are specifically adopted to the AM processes is indicated, as well as for experimental validation is of the models. [19]
Due to a large amount of data, simplified models can be applied to predict part properties. This is represented by a distortion prediction by application of inherent strain based simplified models, which is experimentally proven to deliver sufficient results for prediction of distortion of simple geometries depending on the scan strategy. [20]
Ilin et al show an approach for the modeling of thermal processes during laser beam melting: local heating, melting and solidification are considered to predict the melt pool geometry. The results of the simulation are validated in experiments. [21]
Simulation models are not only applied for the laser melting process itself, but also in the data preparation and in future probably for the post-processing of AM made parts. They range from topology optimization in the design phase towards optimization of scan strategies and prediction of part properties and microstructures. [22]
Certain simulation models have already been transferred to commercial software solutions. They include optimization of the build orientation, support optimization, a mechanical simulation that calculates residual stresses and distortion, deducing pre-distortion of parts from this simulation. [23]

3.2 Commercial process monitoring systems

All manufacturers of SLM machines include or offer some process monitoring tools for their systems. The different manufacturers apply different approaches, mostly using optical measurement systems. Tab. 1 gives an overview of the solutions offered by the different machine suppliers and the measured parameters.

The systems applied can be divided into five categories: condition monitoring, powder bed monitoring, laser power monitoring, melt pool monitoring, and documentation of the individual layer surfaces.

The condition monitoring applies various sensors to analyze the current machine status. Here parameters are measured that are essential for the safe operation of the machine, like temperature, oxygen content, and gas flow. When the values of certain parameters exceed predefined thresholds, the process is stopped, e.g. when the oxygen content in the build atmosphere is too high [24]. Other parameters are only recorded or give an implication for necessary maintenance activities.

The powder bed monitoring is applied to supervise the application of new powder layers. Some of these systems are capable to react on certain process conditions, like calculating the amount of powder that is applied in each layer [27] or repeating the powder coating, when failures are detected [25].

Values of the laser power monitoring and of the melt pool monitoring are recorded and presented position-dependent. This enables the machine operator to identify areas of the final part, in which the laser power or melt pool behavior differs from the standard values. While all systems use a photodiode for measuring the laser power, different approaches are applied for the melt pool monitoring. Therefore, either photodiode- or camera-based systems are used. Cameras do the capturing of the individual layer surfaces after the melting of each layer. These images are collected and evaluated manually.

Table 1: Available process monitoring systems of different machine suppliers.

Machine manufacturer Monitoring system; sensors	Measured parameter
EOS GmbH [24]	
- EOSTATE Exposure OT; sCMOS camera	- energy input in the melt pool, heat distribution
- EOSTATE MeltPool; photodiodes	- light emission of the melt pool
- EOSTATE PowderBed; camera	- images of the powder layer surface
- EOSTATE System; various sensors	- machine status
SLM Solutions Group AG [25]	
- Melt Pool Monitoring; photodiodes	- heat radiation of the melt pool
- Laser Power Monitoring; photodiode	- actual laser power
- Layer Control System; camera	- images and evaluation of the powder layer surface
DMG Mori [26]	
- Layer Monitoring; camera	- images of the powder layer surface
- Monitoring of the individual layer surface; camera	- images of the molten layers
- Sensor Log [1)]; various sensors	- machine status
Concept Laser GmbH [27]	
- QM Meltpool 3D; photodiode, camera	- melt pool emission and melt pool surface
- QM Coating; camera	- images and evaluation of the powder layer surface
- QM Live View; camera	- video of the build process
- QM Fiber Power; photodiode	- actual laser power
- QM Atmosphere, QM Documentation; various sensors	- machine status
Renishaw plc [28]	
- InfiniAM Central; various sensors	- machine status
- LaserVIEW; photodiode MeltView; photodiodes	- actual laser power melt pool emission
TRUMPF GmbH + Co. KG [29]	
- Process Monitoring, Powder Bed Monitoring; camera	- images of powder layer surface and molten layers
- Condition Monitoring; various sensors	- machine status

[1)] equipment of laboratory machine SLM 125, no information available on the company website

4 EVALUATION

For the application of process monitoring systems and especially the further development towards process control, it is necessary to prove the significance of the measured parameters for the part quality. Different researchers prove that melt pool emissions change in areas, where final parts show failures [13, 14, 15]. In addition, evaluations of commercial systems exist. The systems EOSTATE Meltpool and EOSTATE Exposure OT are evaluated regarding the opportunities to detect mistakes during the build process by intentionally producing substandard parts. The comparison of the data from the substandard process to those of a standard process show differences in the mean values and in the standard deviation. [30]

Nevertheless, a full proof of the applicability would also require the evaluation of the complete data. It is necessary to compare the changes in the signals that are detected in areas with failures to the overall variation of the signals. At the current state, the systems are mainly collecting data, which is evaluated manually afterward. Changes in the signals are used as indicators for final part inspection. For parts that are produced in larger numbers, it is possible to compare the data of a larger number of parts to come to threshold values. But this is not feasible for individual parts or very small lot sizes. Here, it is necessary to find a possibility to define general thresholds.

For the development towards process control, it is necessary to identify the process parameters with the strongest influence on the part quality [31]. As presented in chapter 2.1.1, it is still difficult to identify the most influencing factors, as research work uses different approaches and some results are contradictory.

In an experimental setup, a definitive screening is used to evaluate the influence of a larger number of parameters and of parameter combinations. Tensile bars from tool steel are built on a Realizer SLM 125 machine and the parameters of the exposure strategy are analyzed regarding their influence on part density and tensile strength. The individual p-value is used to evaluate the probability, that a parameter has an influence on the measured variable. Fig. 1 shows the effects of the parameters with the highest influence.

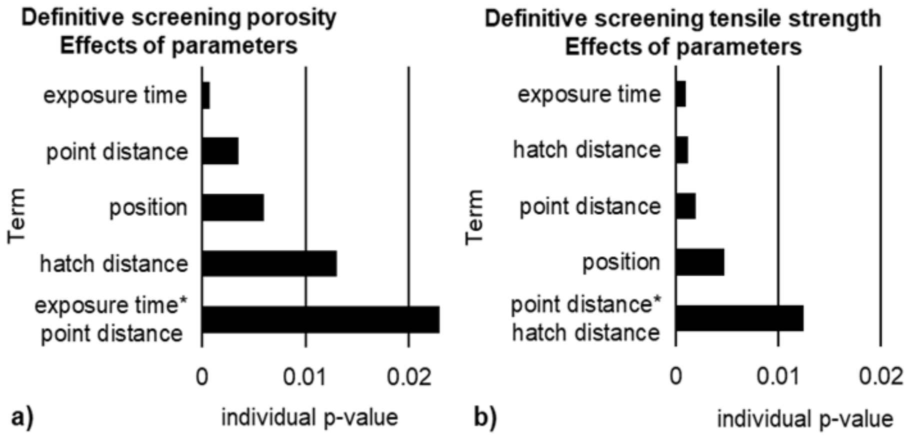

Figure 1: Effects of parameters on a) porosity, b) tensile strength.

A lower p-value means a higher probability, that the parameter influences the measured variable. A common threshold for indicating an influence is 0.05. Following this definition, some of the parameters can be expected to have an influence on the properties of the parts. Nevertheless, the individual p-value can only be a first indication for the identification of the most influencing factors. Further research is required on the influence of these parameters. To enable the application of the results for process control, it is also necessary not only to identify the influencing factors but also to find the mathematical correlation between the parameters and the process results. Furthermore, the evaluation has to be extended to different materials, especially as the first experiments with CoCr material show different results [32].
The application of nondestructive quality inspection methods can also contribute to building a database. Especially predictive modeling approaches that predict the part quality during the build job can be applied to collect additional information by using data mining techniques and supervised learning to analyze logged data during the build process. [33]

5 CONCLUSION

The existing process monitoring solutions show a huge potential to improve the reliability of the SLM process. At the current state, only a few automated analyzing tools are applied. The data is mainly used to evaluate the quality of the built parts or in some cases to stop a build process when obvious failures occur.
To develop the possibilities for process monitoring towards solutions for process control, a complete validation of their applicability is required. Furthermore, influencing factors have to be identified and mathematical

models are needed to explain their correlation with the part properties. A lot of research work is already done in this area, but the results are difficult to compare. The development of certain standards for quality assurance and process capability analysis for additive manufacturing can contribute to an improved comparability. Design of Experiments can be applied to enable the evaluation of a larger number of parameters within a limited number of experiments.
A number of powerful simulation tools exist, that explain the physics of the SLM process. These models use huge amounts of data for their calculation. As this causes long computing times, the simulation tools cannot directly be applied to process control. But they can, on the one hand, contribute to building a database for influencing factors by simulating changes in certain process parameters. And on the other hand, they can be used to develop and verify simplified models, with a lower yet acceptable accuracy, that may shorten the computing time to a degree where the application in the running process becomes possible.

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SESSION B
Direct Digital Manufacturing in the Context of Industry 4.0
Students´ Projects

DESIGN OF AN ALM-BASED PROCESS FOR CONFIGURING PLM SYSTEMS

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Abstract
Companies that use product lifecycle management (PLM) systems need to configure them individually. Such configuration is considered as a software development process. This article demonstrates how the software development process for PLM configuration can be improved by applying application lifecycle management (ALM) concepts. This paper explains how such a concept design can be created and implemented. The concept was evaluated in a real industrial case study. By this, it provides valuable insights useable for any company, facing similar challenges as depicted in this paper.

Keywords:
PLM, ALM, Software engineering, V-model, Scrum

1 INTRODUCTION

Product lifecycle management (PLM) is defined as the business activity of managing a company's products across their entire lifecycles in the most effective way [1]. However, PLM will only work efficiently, if appropriate IT systems are applied and configured specifically for the needs of a company. The configuration of a PLM system is a complex task requiring software development processes. Application lifecycle management (ALM) is a strategy for managing such software development processes. ALM organizes the software lifecycle by "indicating the coordination of activities and the management of artifacts (e.g., requirements, source code, and test cases) during a software product's lifecycle" [2].
This work addresses the respective situation at Phoenix Contact. Phoenix Contact is a leading supplier of electrical components and automation solutions for industrial applications, headquartered in Blomberg, Germany. In more than 50 worldwide subsidiaries, 16,000 employees develop, manufacture, and distribute more than 60,000 products to various industrial markets. All of these products are managed in a so-called PLM system.
The IT department of Phoenix Contact, which is in charge to maintain the PLM system, today applies an inhomogeneous tool landscape with different tools for requirements management, defect tracking and test management.
Use cases and requirements are modeled in Enterprise Architect (EA), a UML modeling tool [3]. UML stands for Unified Modelling Language [4]. The

software project management as well as the test management is mapped in JIRA [5]. Entire projects and the associated error management can be organized with this tool. Furthermore, for other purposes still classic documents (MS Word, MS Excel) are used.

This disconnected tool chain leads to several problems such as inefficient project management, lack of traceability, training of many tools etc. Furthermore, as the functional scope of the systems partly overlaps, it is for the team members unclear, which tool to use for which purpose.

The aim of the work described in this paper was to design a process that is applied in one single ALM system, namely Polarion ALM [6]. The focus lays on the identification of all artifacts, which are today in EA and/or JIRA and map theses artifacts to Polarion artifacts. Furthermore, it shall be proofed, that the new concept fulfills the need of the IT department.

Section 2 briefly introduces the V-model and the Scrum model as the main software process models. Section 3 shows the developed process design and presents it together with the distribution of tasks among the stakeholders. In section 4 the process design is evaluated, and examples of the workflow are shown. Finally, Section 5 outlines the conclusion and presents an outlook on future work.

2 RELATED WORK

The V-model shows a software development process based on a planned approach (Figure 1). Originally, Barry Boehm developed this model as an advancement of the Waterfall model [7]. It defines a project strategy that among others regulates a chronological sequence and the necessary quality level in the form of milestones. The goal is to develop a high-quality product in an environment with complex tasks and systems [8]. The starting point is a clearly defined development order, which is documented in the form of requirements. These requirements are used to evaluate the product at the end of the development process. The aim of the system design is to define a cross-domain solution concept. It describes the central physical and logical effects of the future product. The overall functions are divided into sub-functions, which are assigned to the solution elements. These functions are checked in the system context and combined to form an overall system. Validation and verification are integrated into the general V-model. The validation checks the validity of the system according to whether the system is suitable for the purpose. Where against verification checks the correctness of the system [9]. The respective specific solution concept is continuously tested for compliance with the requirements and the previously defined system properties.

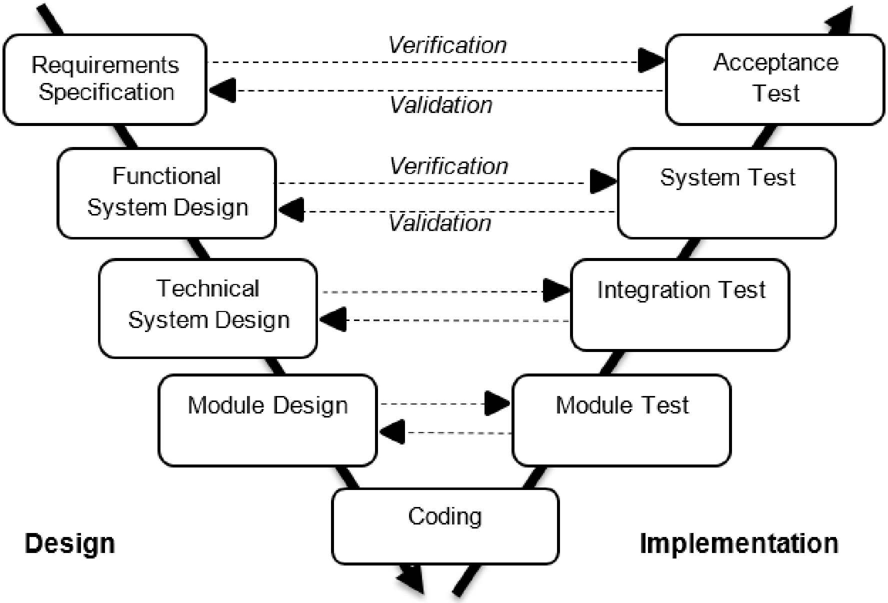


Figure 1: The general V-model [10].

The Scrum process model is based on an agile approach that focuses on administration in the form of iterative developments (Figure 2). Scrum is divided into three phases. The first, general planning phase defines the overall objectives of the project. In the second phase, an agile team performs a series of repetitive sprint cycles [11]. However, after extensive testing, part of the software project goes online in each cycle. In the third phase, the project is completed, and an overall review takes place with all project participants. The advantages of the method are the iterative approach. At the beginning of a new development project, there are many uncertainties: What are the requirements? Which steps are necessary? What will the product look like in the end? Scrum meets these uncertainties by creating only a rough plan at the beginning. The requirements are permanently collected in the product backlog and processed gradually in the sprints [12]. Therefore, Scrum is ideal for research and development projects with a high degree of innovation as well as for high-risk projects with many uncertainties because the method gradually approaches the goal [9].

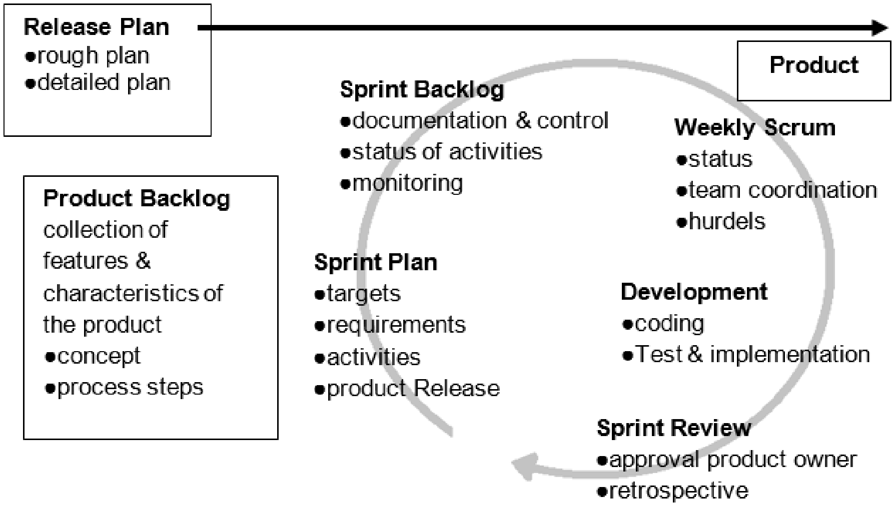


Figure 2: Scrum process model according to [13].

3 ALM-BASED PROCESS DESIGN

The approach in this work was to take out the advantages of both methods, the V-model and the Scrum-model, and to combine them. This work designs a combination of a process model and a system model: The process model depicts all artifacts, which are created in the software development process and their relations. Examples are requirements, test cases and the links between them. The system model depicts the activities, roles, and responsibilities needed to establish the process model. The process model in this work bases on the V-model and the system model bases on Scrum (Figure 3). The design also considers the specific project structures of Phoenix Contact, which were determined during this work using an actual state analysis. Furthermore, the designed approach takes into account the existing configuration of Polarion in the product development teams. This ensures a reuse of knowledge within the company.

Polarion is web-based and supports agile and traditional software development methods. It is a tool for requirements collection, change management and test management with the subsequent troubleshooting.

In Polarion, artifacts are called “work items” and there are different types of work items like the requirement, use case or test case. Such work items are freely configurable by a company using this tool.

Important points in the process flow include traceability, iterative sprint planning, configuration options for workflows and work items, and agile reporting. An assignment of rights in relation to the folder structures and the possible applications of the individual stakeholders was also important to ensure an orderly project flow in this agile environment.

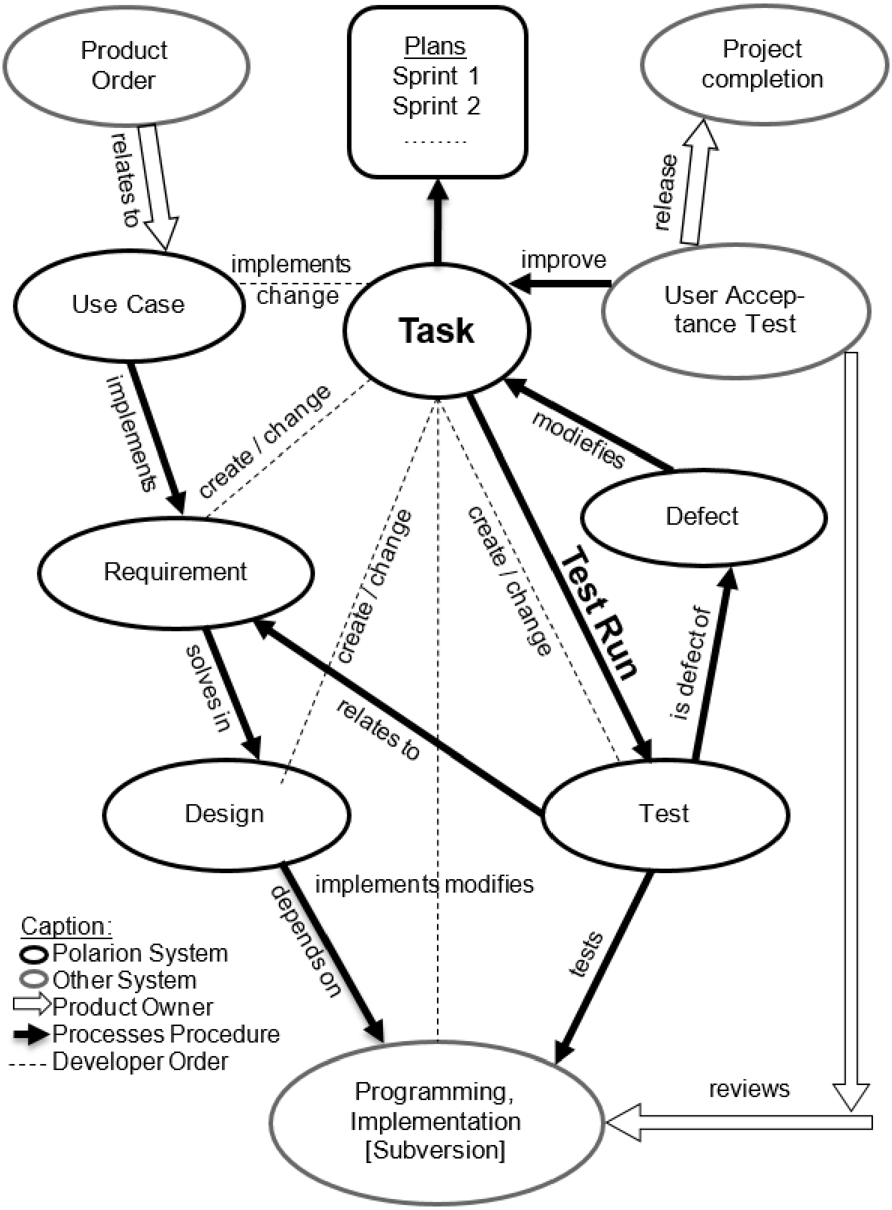


Figure 3: Process design for an ideal workflow.

Table 1: Role and task distribution in process design.

Distribution of roles	Distribution of tasks
Product Owner	Use case-, Requirement creation User acceptance test (UAT)
Requirements Manager	Use case-, Requirement-, Design-, Test case creation
Developer	Design creation, Programming/coding, implementation
Project Manager	Workflow- and Item-Configuration, Assignment of rights, release planning
Testers	Test run execution, defect creation

The process flow consists of several steps performed by different roles (Table 1). In the beginning, there is the order from an internal company department - or, if an abstract project is considered, the customer. In the beginning, a product owner creates the first requirements and functionalities in cooperation with the requirements manager. The requirements manager should use the "Easy Approach to Requirements Syntax" method to create and differentiate the requirements. This is an effective method for formulating good quality requirements [14]. The product owner then steps back but remains available for further inquiries, agreements, and the use acceptance tests. It is recommended that the product owner immediately creates the first requirements in Polarion. This helps other stakeholders to understand how the requirements arise during the project. Polarion tracks all changes in a history function, which helps to recall decisions made a while ago. Another advantage of the proposed process design approach is traceability, as each step is linked to the previous and subsequent steps. In this way, every stakeholder can follow certain decisions and changes.

The developer in cooperation with the requirements manager does the technical system design. This is usually realized using UML. This includes class diagrams as well as activity diagrams. Once the responsible persons approve the UML-artifacts, the process continues with the programming and implementation phase.

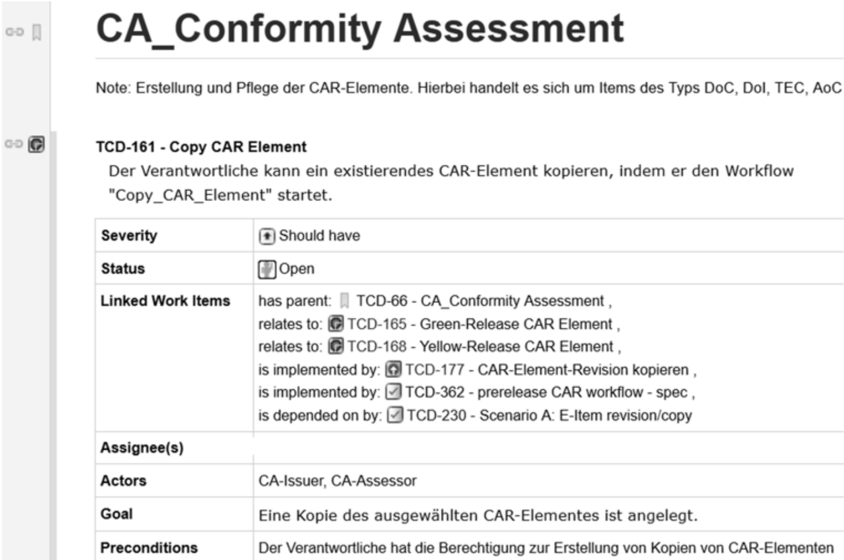
In Polarion, the project teams divide the whole project into sprints following the Scrum-model. For this, it creates and assigns so-called task work items to a sprint (see Figure 3). If certain tasks did not finish in a sprint, the team moves them to the next sprint. Reasons can be complications with the integration of functionalities, programming errors or changing requirements of the process owner. An update of the PLM system to be configured, with associated code and component changes, could lead to further integration problems.

The task items represent task instructions and the distribution of change requests in relation to the other work items in the project. An example of a task is: "Create the requirements". Such a task item links then to all requirements work items, which are created as the result of this task. In addition, the project manager controls the entire project or individual sprints as intended. The extent to which the task items are used depends greatly on the structure and procedure of the team. If a stakeholder lacks rights to change use cases, requirements or design items, this stakeholder has the option of creating a task item and assigning it to the corresponding responsible stakeholder. This is entrusted with the task of changing a design item, for example. It makes sense to create a link between the task item and the design item so that there is no task confusion. The creator of the task item also specifies how much time he or she will allow completing the task. The assignee of the task then specifies the actual amount of time required.

4 IMPLEMENTATION AND EVALUATION

The evaluation of this process design took place in a transfer of a completed real project, the so-called “CA_Conformity Assessment”. This project, which has already been implemented with the tools Enterprise Architect and Jira, was transferred to Polarion using the new process design.

Figure 4 shows a section of the live document “CA_Conformity Assessment”. The assigned use case contains a short description and provides information about the current status, the assignee and the items linked to the use case. In addition, the use case target, the preconditions and the actors belonging to the use case are displayed. The work item properties in the document view can be used to individually configure properties such as creation date, author, destinations, estimated time, and so on.



CA_Conformity Assessment

Note: Erstellung und Pflege der CAR-Elemente. Hierbei handelt es sich um Items des Typs DoC, DoI, TEC, AoC

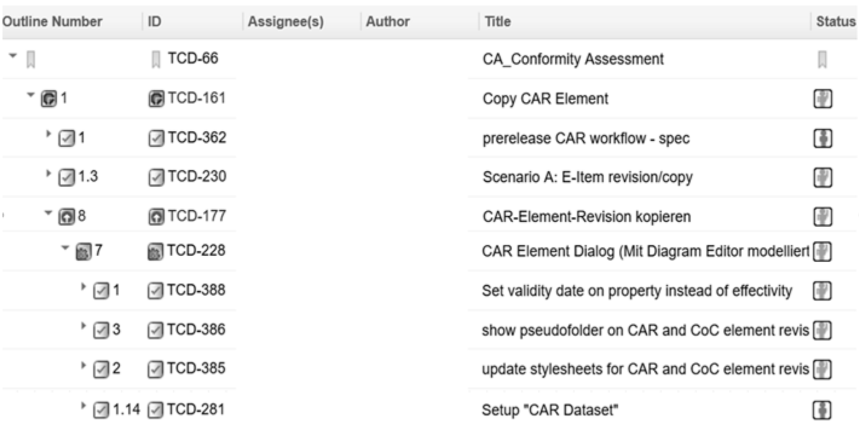
TCD-161 - Copy CAR Element

Der Verantwortliche kann ein existierendes CAR-Element kopieren, indem er den Workflow "Copy_CAR_Element" startet.

Severity	Should have
Status	Open
Linked Work Items	has parent: TCD-66 - CA_Conformity Assessment , relates to: TCD-165 - Green-Release CAR Element , relates to: TCD-168 - Yellow-Release CAR Element , is implemented by: TCD-177 - CAR-Element-Revision kopieren , is implemented by: TCD-362 - prerelease CAR workflow - spec , is depended on by: TCD-230 - Scenario A: E-Item revision/copy
Assignee(s)	
Actors	CA-Issuer, CA-Assessor
Goal	Eine Kopie des ausgewählten CAR-Elementes ist angelegt.
Preconditions	Der Verantwortliche hat die Berechtigung zur Erstellung von Kopien von CAR-Elementen

Figure 4: Use-Case “Copy CAR Element” in the document view of the document “CA_Conformity Assessment”.

Figure 5 shows an example of the implementation of the process model in Polarion. The use case “Copy CAR Element” is implemented among others by the requirement “Copy CAR Element Revision”. The design item „CAR Element Dialog” implements this requirement. The link relationship “solves in” is used. However, it is not visible due to the filter settings of the displayed view.



Outline Number	ID	Assignee(s)	Author	Title	Status
	TCD-66			CA_Conformity Assessment	
1	TCD-161			Copy CAR Element	
1	TCD-362			prerelease CAR workflow - spec	
1.3	TCD-230			Scenario A: E-Item revision/copy	
8	TCD-177			CAR-Element-Revision kopieren	
7	TCD-228			CAR Element Dialog (Mit Diagram Editor modelliert	
1	TCD-388			Set validity date on property instead of effectivity	
3	TCD-386			show pseudofolder on CAR and CoC element revis	
2	TCD-385			update stylesheets for CAR and CoC element revis	
1.14	TCD-281			Setup "CAR Dataset"	

Figure 5: Link relationships in the tree view that refer to the use case “Copy CAR Element”.

Depending on the use case and design item, the created task items are displayed. For example, the task item “update stylesheets for CAR and CoC element” contains the change request for the design item “CAR Element Dialog”. The task item also gives the change request for the “CoC Element Dialog” design item, which is shown in the following Figure 6. So, a task item has been created, indicating that two design items are being changed. This can be seen in the links of the task item. In addition, a relationship is highlighted by linking "relates to" to two other design items.

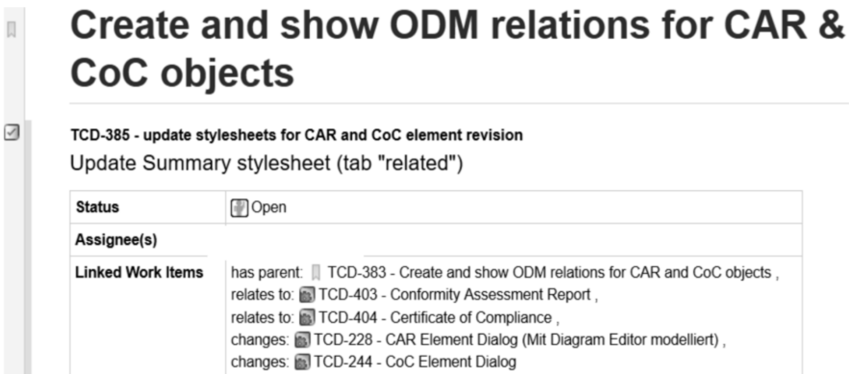


Figure 6: Example of a Task-Item with the linked Design-Items in the document view.

The project, which was transferred to Polarion, was presented to selected stakeholder at Phoenix Contact. They confirmed, that all project artifacts, which today are managed in JIRA and Enterprise Architect, are completely manageable in Polarion. The great advantage of the proposed design is to have all artifacts in one single tool.

5 CONCLUSION AND FUTURE WORK

Companies like Phoenix Contact have to constantly revise, adapt and improve their PLM processes. ALM tools such as Polarion help in the areas of documentation, traceability, project management, and team communication. Today, teams are increasingly not working in one location; they are split all over the world. Agile project management is particularly relevant because it delivers faster results and is more flexible. According to the results of the present work, this is exactly the right response to global market requirements and the associated competitive pressure, which is reflected in a predetermined, tight budget and deadline compliance targets.

The developed design was implemented in a real industrial project in order to show the advantages of the new solution. This paper explains how the new procedure was created, implemented and evaluated. Although it shows a special industrial showcase, it offers valuable insights that can be used by any company and pose challenges similar to those presented in this article. On the one hand, it is based on the V-model, but on the other hand, in large part, on agile software development using the Scrum method. It may well be discussed to structure individual work items differently or to name link relationships differently, but overall the ideal process sets the direction for project work with Polarion. Upon completion of this work, Phoenix Contact was provided with a concrete recommendation for future project work. It should be emphasized that one can implement the process with only one tool, which prevents an inhomogeneous tool landscape.
Further research should deal with the reporting of projects related to Polarion. In addition, the approval process can be examined more in detail. Here, however, the respective corporate philosophy must always be considered.

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ANALYSIS OF INFLUENCING PARAMETERS ON MECHANICAL AND PHYSICAL PROPERTIES OF SLM PARTS

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Abstract
Since additive manufacturing (AM) is continuously growing, the influence of processing conditions and setup parameters on microstructural and mechanical properties of additively manufactured components needs to be clarified. The paper discusses an experimental approach for the identification of influencing parameters in Selective Laser Melting; this consists of an evaluation of the mechanical and physical properties of final parts, depending on the chosen process parameters. The Design of Experiments is used to get valid results from a limited number of experiments. The research work focuses on the application of a Definitive Screening Design to identify the most important influencing parameters: Several parameters of the hatch and the contour exposure are varied, as well as the position and orientation of the samples in the build chamber. A maraging steel and a CoCr alloy are used, and the mechanical and physical properties of the samples are evaluated. The interdependencies between the variation of the factors and the observed properties are analyzed.

Keywords:
Additive manufacturing, Process parameters, Design of Experiments, Density measurement

1 INTRODUCTION

Selective Laser Melting (SLM) is a powder-based additive manufacturing process. During the process, successive layers of metal powder are molten and consolidated on top of each other by the energy of a laser beam. In the end, almost fully dense parts are produced. Typical examples to reveal the scope of the application areas of this process are customized medical parts (bio-engineering), tooling inserts with conformal cooling channels (machining) and functional components with high geometrical complexity (mechanical and aerospace). [1]
For this research work, a Realizer SLM 125 machine is used to perform all the required build jobs.

2 THE PROCESS PARAMETERS

The most important SLM process parameters are described in this chapter. These are not the only parameters that have to be set before the start of a build job but are the ones on which this research work is focused on.

- Exposure Time: It is the time (in µs) the laser remains at the same point on the powder bed.
- Point Distance: The laser beam is not moved continuously, but from point to point along the path. The point distance is the distance (in µm) between two successive stops.
- Laser Current: It is the current (in mA) that feeds the laser. It is directly connected to the laser power.
- Lens Position: This parameter refers to the position adjustment of the focusing lens, in correlation with the X-Y scanning mirrors, so that the focus distance is the optimum one. If the focusing lenses are not in the right position, the focus plane will be situated above or below the powder surface.
- Hatch Distance: The hatch distance (or hatch spacing) is defined as the distance between parallel laser scans. The ideal hatch spacing will be dependent on the melt pool size and the laser spot size. It should be large enough to decrease runtime but still small enough so that there is some re-melting between parallel laser passes.
- Hatch Offset: The hatch offset is the distance between the hatch scans and the contour of the part. This distance, if the value is too high, could cause a non-perfect melting of the inner cross-section particles with the boundaries, causing porosity between the contour and the hatch zones.
- Hatch Rotation: The hatch rotation angle defines the raster-changing angle between two subsequent layers. It is easy to figure out how it is hard to eliminate the anisotropy of mechanical properties if improper hatch angle is adopted and thus affecting the whole performance of the fabricated parts.
- Fill Line Distance: This parameter represents the distance between the contour scan and the fill line scan. This secondary laser scan, which is parallel to the contour scan, could be required or not, depending on the material used. In this research work, the fill line and the fill line distance parameters have been only set for the CoCr sample (as suggested by the machine producer).

3 MARAGING STEEL

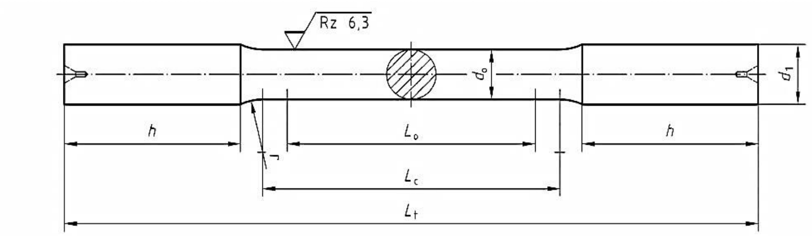
In the first part of the work, the mechanical and physical properties of an SLM made maraging steel have been analyzed.

3.1 Material characterization

This steel (also known as 18Ni-300, 1.2709 Steel or Tool Steel), which uses nickel as the primary strengthening element instead of carbon, is known for its high strength and toughness. Despite its high strength, the material can be easily machined or formed and after these treatments, it can undergo an aging (heat treatment) step that forms intermetallic precipitates involving cobalt, molybdenum, and titanium, which aid in increasing the tensile strength. Due to the high nickel content, the alloy has high hardenability and has wear resistance that is suitable for many tooling applications. The material can be heat treated in air at low temperatures and because of the low thermal coefficient of expansion, has excellent dimensional stability. The low carbon content also helps when used in SLM since the material is not susceptible to thermal stress cracks during cooling. [2]

3.1 Tensile test

The first experiment is set up to investigate the mechanical properties of 1.2709 steel in the fabrication of 27 tensile test specimens according to the DIN 50125 [3]. The edition of the norm used specifies examples of tensile test piece shapes, which meet the overall conditions specified in DIN EN ISO 6892-1 [4]. Figure 1 and Table 1 show the dimension used for the specimen.



Key

d_o	test piece diameter	L_o	original gauge length ($L_o = 5\,d_o$)
d_1	diameter of gripped ends ($\geq 1{,}2\,d_o$)	L_c	parallel length ($L_c \geq L_o + d_o$)
h	length of gripped ends	L_t	total length of test piece

Figure 1: Type A test piece, of circular cross-section, with smooth, cylindrical ends for clamping in wedge grips.

Table 1: Geometrical dimensions of the tensile test specimen.

d_0	L_0	d_1	r	h	L_c	L_t
[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
4	20	5	3	18	24	60

The SLM process has a very large number of parameters that have to be set up for correct operation of the build job. For this reason, it becomes necessary to select the right parameters to get an acceptable scope of experiments. A designed experiment is a controlled set of tests designed to model, find, and explore the relationship between factors and one or more responses. The software used is JMP PRO 13. The entire design space is divided into three blocks with nine samples each, for a total of 27 samples. The setup parameters and the relative imposed value are presented in Table 2.

Table 2: Set up values for each parameter.

Parameter	**Unit**	**Lower value**	**Mid value**	**Upper value**
Exposure time	[µs]	24	40	55
Point distance	[µm]	30	40	50
Laser current	[mA]	2700	3000	3300
Lens position	[mm/100]	220	260	300
Hatch distance	[µm]	0.08	0.10	0.12
Hatch rotation	[°]	10	45	90

All 27 specimens are tested using a tensile testing machine, and a log file with all the results and the stress-strain curves for each specimen is saved at the end of the tests**.**

3.2 Density measurements

It is commonly known that all powder-based processes, depending on the process parameters, provide a specific porosity in the part. So the most economical way to get information about the mechanical parameters is the measurement of the density of the part, as the porosity directly affects the mechanical strength, fatigue strength and the elongation to rupture. [5]
To measure the density of the bars, the Archimedes method is chosen, using a precision scale.

4 COBALT-CHROME SUPERALLOY

This second experiment is set up to investigate the dependencies between the SLM machine parameters and the resulting porosity of CoCr built parts. Since this is the first build job with the CoCr alloy in the SLM machine of the Smart Factory laboratory, it is necessary to determine which combination of machine parameters gives the best results in terms of density.

4.1 Material characterization

Cobalt-base alloys are designed around a cobalt-chromium matrix with chromium contents ranging from 18 to 35 wt %. The high chromium content contributes to oxidation and sulfidation resistance but also participates in carbide formation and solid-solution strengthening.
This superalloy is nowadays largely used in biomedical applications, as prostheses for orthopedic and dental implants. [6]

4.2 Density measurements

This build job is set up for the building of 25 cubic samples. These samples have the dimensions of 8 x 8 x 8 mm³. This size is chosen in order to lay as many test cubes as possible on the build platform, to have a better overview of how the different machine parameters could influence the density of the parts.
The required Design of Experiments is created with the Definitive Screening Design platform, to find out which parameters are responsible for the porosity of the parts. For each parameter, 3 values are set, and the design space is divided into 5 blocks to take into account also the position of the parts on the build platform, as displayed in Table 3.

Table 3: Set up values for each parameter.

Parameter	Unit	Lower value	Mid value	Upper value
Exposure time	[µs]	40	45	60
Laser current	[mA]	1320	1360	1400
Lens position	[mm/100]	100	120	140
Hatch distance	[µm]	0.06	0.08	0.10
Hatch offset	[µm]	0.02	0.03	0.04
Hatch rotation	[°]	10	45	90

As previously described for the density measurements of the tool steel samples, the Archimedes method is used. In this case, to make a comparison between two different methods of density calculation, a metallographic analysis of the samples is performed, too.
To characterize the porosity and to have an overview on how these defects were distributed inside the samples, a micrographic analysis of an inner cross-section of the four best and of the four worst performing samples in terms of porosity, is conducted. This requires a specific preparation of the samples. After the grinding and polishing, four images of each sample are taken. Using a lower magnification, 50 X, it is not possible to capture the entire cross sections with less than 20 pictures, so it is decided to analyze four images on

the four corners of the samples, called NW, NE, SE, and SW, using a geographical notation.
This step is the starting point for measuring the porosity of the samples by measuring the total area of the pores inside the sample's cross-sections.
First of all, a single image is selected, and a rectangular area is drawn (Fig. 2); then, the right threshold value is set to convert the image from greyscale to black and white. At this point, the software automatically calculates the total area of the black pixels (the pores) and of the white pixels (the fully dense material). It has to be noticed that this method for calculating the density gives a local overview of the pores only in one cross-section of the sample. The calculated density of the parts via metallographic analysis is very precise referred only to one specific cross-section.

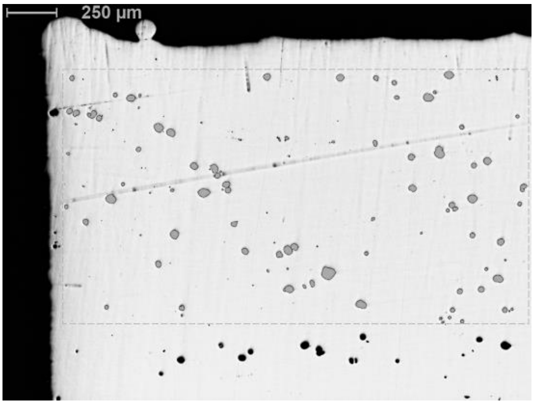


Figure 2: Example of the rectangular area for the porosity calculation.

The rectangular areas are kept constant for all the processed images. The values of the porosity for each sample are then calculated by measuring the value of the four corner images for every sample and then calculating the average value for the entire cross section.

5 PART QUALITY REPEATABILITY

After identifying the machine parameters that ensure the best performing samples in terms of porosity, a new need rises with the repeatability of the part quality. Because of the large number of machine parameters, their interactions, and the particular atmosphere that has to be set up during the building process, it is very important to be able to reproduce the same mechanical and physical characteristics for each part using the same process parameters.

To investigate this important quality feature, two new identical build jobs are performed. Taking into consideration the results of the density measurement of the previous build job, the three samples with the highest density are used as a base for these new jobs. The samples #3, #2 and #4 with the relative settings are positioned on the build platform using the pattern visible in Figure 3. As it is possible to see, the positions are labeled using a geographical notation as C, NE, SE, SW, and NW. These positions are then renamed as 1, 2, 3, 4 and 5 respectively, for an easier data analysis.

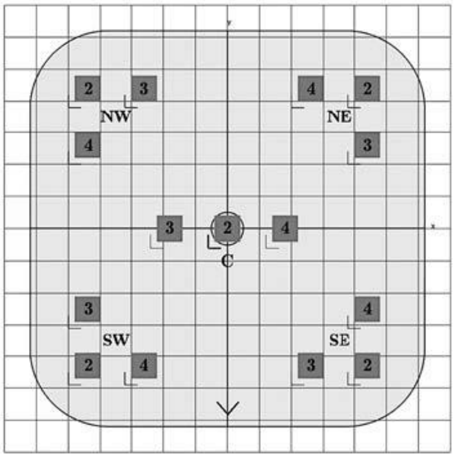


Figure 3: Map of the samples on the build platform.

Each sample is reproduced on the build platform five times, always with the same process parameters.

6 RESULTS

6.1 Tensile properties of maraging steel

The fit two-level screening platform of the statistical software is used to find out and to characterize the correlations between a result and a group of parameters on which this result depends. In the following pictures (Fig. 4-6) are presented the correlations between the tensile properties (UTS, yield strength, and Young's Modulus) and the process parameters used. The factors highlighted in these plots are the ones with the biggest influence on the relative results.

It can be seen, that the parameters exposure time, point distance, and hatch distance have the strongest influence on all three measured tensile properties. It has to be noticed that these important results are only valid for the used set up values. Further experiments with different machine parameters values are needed to extend these outcomes and conclusions.

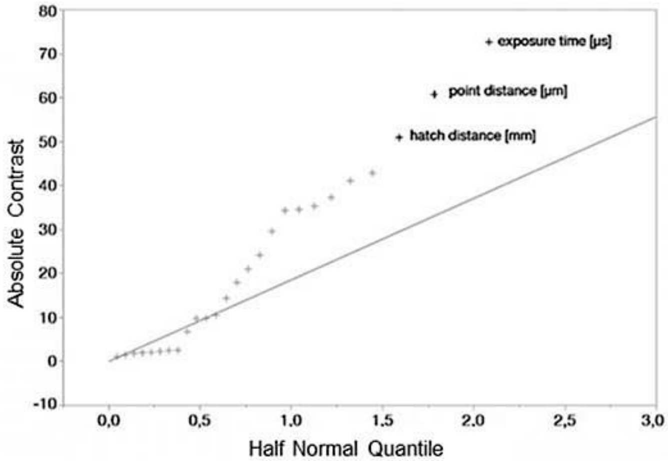


Figure 4: Half-normal plot of the measured UTS.

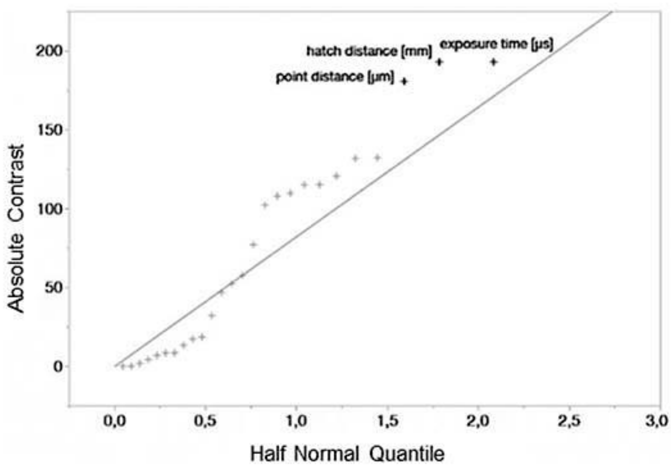


Figure 5: Half-normal plot of the Young's Modulus.

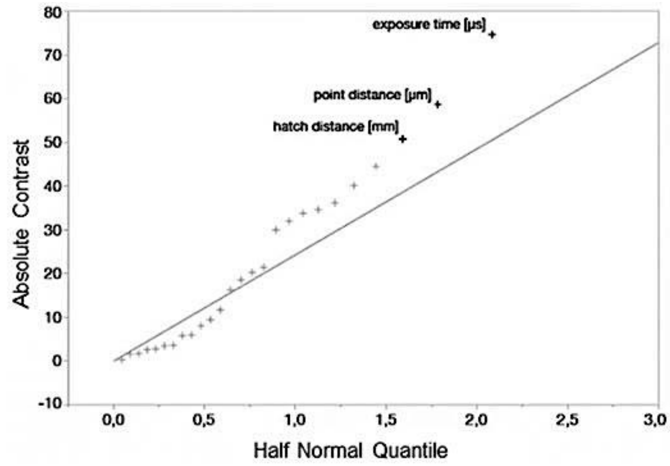


Figure 6: Half-normal plot of the measured Yield strength.

6.2 Density of CoCr alloy

The following Table 4 sums up the density results calculated with the two methods adopted.

Table 4: Comparison between the porosity measured using the Archimedes method and the metallographic analysis.

	Samples							
	03	*02*	*08*	*04*	*19*	*13*	*20*	*01*
Method	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Archimedes method	0.67	0.71	0.87	0.88	1.39	1.45	1.64	2.12
Metallogr. analysis	0.39	0.10	0.10	0.41	1.94	0.37	3.63	0.28
Absolute value of the difference	0.28	0.61	0.77	0.47	0.55	1.08	1.99	1.84

In this table, samples 03, 02, 08 and 04 are the four best samples in terms of density according to the Archimedes method, while samples 19, 13, 20 and 01 are the worst ones. As it is possible to see, the absolute value of the difference between the results of the two mentioned method is lower for the first four samples compared to the last four samples.

The Archimedes method gives a less detailed but more complete result of the density of the entire sample. However, the metallographic analysis is more profitable to understand and characterize the porosity of the samples, but at the same time, it is very precise only referred to a singular cross-section of the sample.
It is thus possible that the metallographic analysis of the four worst samples (samples 19, 13, 20 and 01) do not allow to see and analyze other hidden pores inside the parts, and so the difference of density calculated with this method compared to the density calculated with the Archimedes method is very high.

6.3 Repeatability of CoCr alloy

Looking at the achieved data about the porosity of the parts it emerges how the worst results are obtained in the position NE, while the best results are achieved in the position NW. The other results are in the first half of the range. In the map visible in Figure 7, the black color in the top-right area indicates an area of the build platform in which the built parts showed a higher porosity, while the white color of the bigger area on the left represents an area in which the built parts showed a lower porosity.

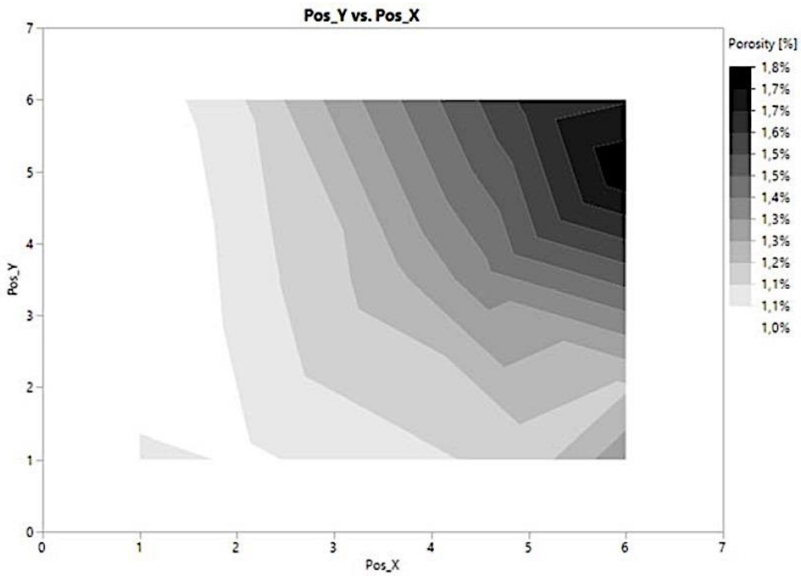


Figure 7: Contour map of the porosity values of the samples depending on the build position on the platform.

The porosity value variation and the alleged dependence between the porosity and the build position could be better analyzed by making a bivariate Fit between these two sets of values. In Figure 8 a linear fit of porosity values by the build position on the platform is plotted using JMP (the correlations between the x-axis values and the build positions visible in Fig. 3 are explained as follows: C=1, NE=2, SE=3, SW=4, and NW=5).

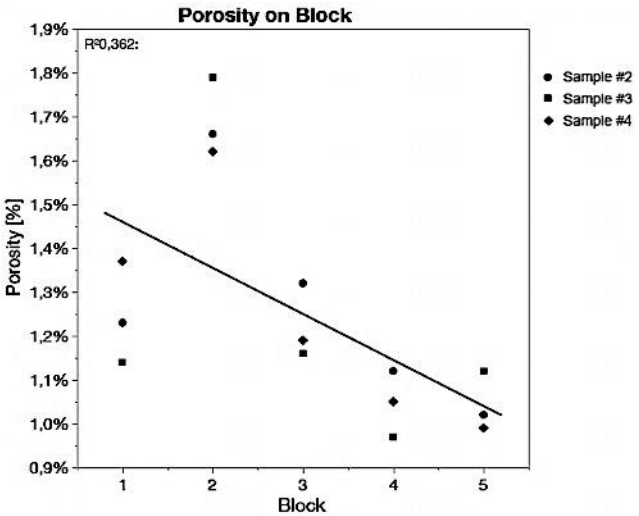


Figure 8: Linear Fit of porosity values [%] depending on block position.

As it is possible to see, the variation decreases, following a clockwise rotation between the NE position to the NW position on the build platform. To analyze if the dependence between a result and a process parameter is strong enough, the first value to look at is the R^2; for this linear fit, its value is R^2=0.362. This value is not so high but identifies a not negligible dependence of the porosity of the parts by changing their build position.

Making a polynomial quadratic fit, the R^2 increases: it switches from a value of R^2=0.362 to R^2=0.448. In Figure 9 the polynomial quadratic fit of porosity on the block position is shown.

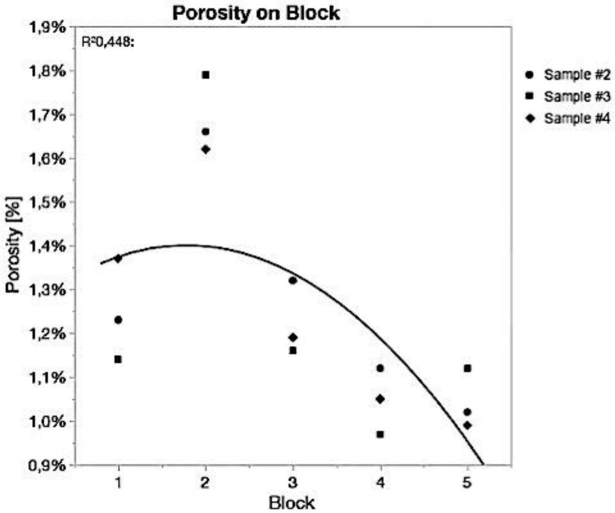


Figure 9: Quadratic Fit of porosity values [%] depending on block position.

It has to be noticed that this kind of approach could be used by setting only the build position as a changing parameter (in the initial DOE design), while all the other process parameters have to be kept constant.
This particular behavior could be attributed to the movement of the wiper during the recoating sequence. In the Realizer SLM 125 machine, the wiper follows a circular movement with an excursion range of about 90°. The position called NW, also marked with number 5 in the previous plots, is the nearest to the rotation center of the wiper. This event could be one important influencing parameter in the final part quality.
The existing SLM machines market shows a higher number of machines that use a linear movement of the wiper instead of a circular movement may be because of the insufficient and irregular part quality pattern produced by the rotational recoating system.
Another build job, designed in the same way and with the same machine parameters is also performed. The achieved results showed the same porosity pattern of the parts on the build platform.
The contour map (Fig. 7) could be also used to analyze and also predict in which zone of the build area the samples could be characterized by a low porosity. This is the starting point for a future optimization of the built part quality.

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SELECTIVE LASER MELTING – CoCr APPROACH: ANALYSIS OF MANUFACTURER PARAMETERS VERSUS RESEARCH RESULTS

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Abstract
Selective laser melting is a powder bed fusion technology that uses a laser as an energy source in order to directly build fully dense metal parts. Optimal fabrication requires a comprehensive understanding of the main processing, as it affects the part quality. Wherefore, the objective of this paper is to perform a survey, data checking and collecting of provided parameters to compare and contextualize it versus the respective values used in the process by the research studies. The work is focused on cobalt-chromium alloys (CoCr) which are widely used in dental and medical applications. This work focuses on surface quality and hardness as built and after the post-processes. As well, the approaches in bond strength after post-processing are considered, comparing the results made by different manufacturing techniques. Finally, this work compares results acquired in surface roughness as built, and tensile strength of parts made by selective laser melting versus the traditional technique cast, before and after heat treatment.

Keywords:
Additive manufacturing, Material properties, Part properties, Process parameters

1 INTRODUCTION

Additive manufacturing (AM) technology has been slower to mature for the use in dental settings due to its high cost. Recently, however, expired patents have allowed for a large decrease in pricing. The process capability of the whole process, including SLM, has to be developed to an acceptable level to ensure a reliable high part quality. There is a lack of clearly defined requirements for reliable process capability and standard tolerance ranges [1]. While for some direct digital technologies, like CNC milling or turning, the achievable accuracy and repeatability have been explored in detail, for newer technologies, especially AM, only a few experience-based values exist. Furthermore, the characteristics of AM processes cause a number of specific issues for quality management, like handling a large number of process parameters. This situation, together with the limited availability of design rules and specified tolerance classes for these technologies, makes it extremely difficult to achieve a proven process capability. [2]

Although SLM shows promise for fabricating prostheses, they must be tested in both the laboratory and the clinic to ensure that they produce dental restorations of a quality at least equal to those produced by conventional techniques. Important properties include acceptable biocompatibility, good corrosion resistance, low internal porosity, adequate mechanical properties, high hardness, density, and tensile strength.

2 STATE OF TECHNOLOGY

2.1 The SLM process

Selective Laser Melting (SLM) is a powder bed process in which metal powder is spread in thin layers with a typical layer thickness of 20 - 100 µm [3]. For uniform distribution of the powder, a leveling system or a recoater blade is used. With the help of a scanner, the laser is directed across the deposited powder layer and melts the powder. According to the cross-section of the part, the metal powder is selectively exposed to the laser beam in the x-y-plane. In this process, the powder is completely melted along the parts contour and filling. Usually, the sequence of the individual melt tracks follows a pattern, whereby the melt tracks overlap with a certain hatch distance. The volume energy supplied to the powder layer causes not only the exposed material to melt but also reaches areas adjacent to the melt pool due to heat conduction. During solidification of the melt, the individual melt tracks and the already solidified layers below are fused [4]. After selective exposure of the powder bed by the laser beam, the build platform is lowered, another powder layer is applied and the process of melting is repeated. These three steps are iterated until the part is completed. After completion, the part itself is connected to the build platform by support structures. These are necessary for heat dissipation and fixation of the part in the powder bed, especially for supporting its horizontally oriented and overhanging surfaces. That way deformation of the part is prevented. The support structures need to be removed to finish the part.
The SLM process is carried out in an inert gas with a residual oxygen content of less than 0.1 % [6]. Nitrogen or argon is fed into the chamber to avoid undesired interactions of the metal powder with its environment and to protect the melt. Furthermore, secondary products of the process such as weld fume and weld spatter are removed by the inert gas flow around the work area [7].

2.2 Opportunities and limitations for dental application

The widespread application of SLM in the dental industry can lead to a potential use of an AM technology for mass production of highly individual parts [8]. The technology shows some limitations, especially regarding maximum part size and dimensional accuracy. The dimensional accuracy is influenced by the parameters of the SLM process. It is strongly dependent on the layer thickness, the powder grain size, the laser beam’s focus diameter and also by the laser power applied in the process. [1] The dimensional

accuracy of the final 3D product can be significantly jeopardized by many factors; including thermal distortion due to continuous melting and resolidification during the SLM process [9].
Due to the welding process and the structure of the powder material, the surface is rough, compared to common subtractive machining, and has average roughness values of 20 µm [10]. In terms of roughness, the largest improvements can be achieved by a reduction of layer thickness. A reduction from 50 µm to 25 µm comes along with a slightly perceptible decrease of vertical roughness and a significant decrease in horizontal roughness depth. [11] The staircase effect of additive manufacturing is another limitation. The layer-by-layer nature leaves a staircase effect on the finished product unless layering thickness is tuned down to the smallest possible resolution which on the other hand will significantly increase the building time of the structures [12]. Post-processes are inevitable to achieve a smooth and shiny surface, such as sand-blasting, shot peening, manual grinding, and ultrasonic burnishing as will be presented here.
Nevertheless, difficulties such as shrinkage during casting and high hardness of CoCr during milling can be surpassed when using SLM technology [13]. Milling creates unfavorable forces to build structures and has high waste and limited complexity of geometrical forms achieved. SLM enables almost zero chipping compared to milling and very little waste compared to casting [14].
Additive manufacturing by SLM is well suited for the production of metal frameworks as different metal materials can be processed without the use of product-specific tools or molds. This technology is an interesting alternative to conventional precision casting and Computer Numeric Control (CNC) milling or grinding.

2.3 Cobalt-chromium alloys

CoCr alloys, which are used in milling and SLM technologies, not only have an advantage over precious alloys in terms of cost, but also a better biocompatibility compared to nickel-chromium alloys [15]. Furthermore, they exhibit material properties considered suitable for dental reconstructions, such as high strength, high modulus of elasticity, and high corrosion resistance [16, 17]. Crowns produced using SLM technology have been found to have a satisfactory marginal misfit for use in dental prostheses [18], and adequate bond strength to porcelain [19]. Most studies used CoCr as a base metal, the popularity of this alloy is attributed beside its relatively inexpensive cost for the good physical properties, making it an ideal material for certain dental restorations such as crown substructures.

3 LITERATURE RESEARCH

A lot of literature deals with the evaluation of the influence of process parameters on the process results. As no standards for the experimental setup exist, the results of the studies are difficult to compare. While in general, more

than 50 influencing parameters in the SLM process can be identified [20], most research work focuses on the influence of the laser exposure parameters [21, 22, 23]. The exposure parameters can be put together to calculate the energy input or energy density of the SLM process, which is considered as the dominant influencing factor on the porosity and other quality characteristics by several researchers [21, 23]. Nevertheless, other publications show, that the energy density is not the only influencing parameter, as the same value for the energy density, achieved by different combinations of scan speed and laser energy, result in different porosities of samples [24].
In the following sections, research approaches are presented, that especially address SLM produced parts from CoCr.

3.1 Comparison of outcome results for surface quality and mechanical property as built and after post-processing in cobalt-chromium

In [25], Salmi, Huuki, and Ituarte applied ultrasonic burnishing as a post-process on SLM built parts and analyzed the effects on surface quality and mechanical properties.
Ultrasonic burnishing is a formative method at this end, used to improve surface quality and increase surface hardness. The process consists of pressing feed motion hardened steel rolls or balls into the surface of the workpiece being post-processed. It works at high impact frequencies (over 20,000 impacts per second can be achieved) and industry typically uses this technique to finish conventionally produced metal surfaces.
The most relevant variables and process parameters were initially mapped and tested on surface quality and hardness in the ultrasonic burnishing equipment installed in the manual lathe and data served as the ground for the presented analysis. In literature, there is no previous data about burnishing being applied to any AM materials or traditional CoCr. In the proposed solution, the ultrasonic burnishing equipment was installed on a manual lathe to post-process CoCr in additively produced applications. Ultrasonic burnishing is much slower, compared to machining. The process time in ultrasonic burnishing depends heavily on spindle speed and feed rate. The fasted burnishing time in the tests for CoCr was 60 s and slowest one about 250 s compared milling time for the same area is 4 s. [25].
Six samples made from EOS CoCr powder are used. Optimal process parameters for post-processing are around 0.05 mm/r for the feed and 1.5 mm for the spring compression for optimal results. Analysis of the experimental result was performed using “Minitab 16” and analyzed by analysis of variance (ANOVA). [25]

3.1.1 Collection of manufacturer parameters and values used in the process

Table 1: EOSINT M270 technical data sheet.

EOSINT M 270 equipment		
Laser power	**Scan speed**	**Layer thickness**
200 W	7 m/s	20 µm

Table 2: Parameters used in the process. [25]

Laser power	**Scan speed**	**Layer thickness**
195 W	1.1 m/s	20 µm

Table 3: EOSINT M270 - CoCr material data sheet.

Surface roughness and hardness as built	
Ra	4 -10 µm
Hardness	360 ± 20 HV10

3.1.2 Evaluation of results

Table 4 shows the results of the surface roughness and hardness measurements from the experiment.

Table 4: Surface roughness and hardness results as built (EOSINT M 270) and after post-processing. [25]

	Surface roughness Ra (µm)			**Hardness (HV10)**		
	Min	**Max**	**Average**	**Min**	**Max**	**Average**
As built CoCr	4.30	7.81	5.66	367.04	380.63	373.84
Ultrasonic burnished CoCr	0.08	0.20	0.18	520.78	591.02	551.07
Turned CoCr	1.20	1.26	1.24	458.64	458.64	458.64
Turned and burnished CoCr	0.06	0.08	0.07	577.10	583.89	580.50

SLM has limited availability of specified tolerance for frameworks and up to date, it has no defined specifications for surface roughness. [1] The study compares achievable values without linking those to special applications of the parts.

- Average surface roughness (Ra) as built and hardness acquired respectively: 5.66 µm 373.84 HV, attends the manufacturer results provided: Ra 4-10 µm and hardness 360 ± 20 HV10.
- Post-processing by the ultrasonic burnishing method allows a relative increase in the average hardness of 47.4 %, i.e. from 373.84 to 551.07 HV. By ultrasonic burnishing, the surface quality is improved approximately 32 times from as built (from Ra=5.66 µm to Ra=0.18 µm). Values below 0.2 µm, which is a high level of finish and a perfectly smooth surface according to production standard ISO 1302:2002.
- Analyzing hardness considering only milled technique result, it had a relative increase of 22.7 % from as-built 373.84 HV to 458.64 HV. When comparing ultrasonic burnished hardness versus milled plus burnished the difference in increased hardness is not substantial.
- Analyzing surface quality comparing only the milled technique (Ra=1.24 µm) versus ultrasonic burnished (Ra=0.18 µm), the second process achieving values below 0.2 µm, is a high level of finish and a perfectly smooth surface according to production standard ISO 1302:2002 indication of surface texture in the technical product documentation. Evaluating the difference of ultrasonic burnished (Ra=0.18 µm) versus milled + burnished (Ra= 0.07 µm), the second process shows better surface quality, but nevertheless, the difference is not substantial as both processes fall under the same category in the ISO standard.

The study point it out that surface roughness increases with the increase of feed speed and the spring compression need to be not too low or not too high. The increase in the surface hardness is expected to be a result of strain hardening of the sample surface due to the mechanical impact during ultrasonic burnishing. And for both, surface roughness and hardness, the results greatly improve by the effects of using optimal process parameters, specifically in the interaction between feed speed and spring compression [25].

3.2 Comparison of outcome results for bond strength after post-processing made by casting, milling, and selective laser melting in cobalt-chromium

Li et al. in [27] compare different manufacturing technologies for dental frameworks regarding the adherence of the ceramic veneering.
Ten samples of CoCr powder components with dimensions of 25×3×0.5 mm^3 are prepared by casting, milling, and SLM and layered with ceramic in an area of 8×3×1.1 mm^3. Metal-ceramic bond strength is measured by a 3-point bend test. The specimens are measured and prepared according to a defined procedure.

3.2.1 Collection of manufacturer parameters and values used in the process

Table 5: CONCEPT LASER technical data sheet.

CONCEPT LASER M1 cusing equipment		
Laser power	**Scan speed**	**Laser thickness**
200 W	7 m/s	20 - 80 µm

Table 6: Parameters used in the process. [27]

Laser power	**Scan speed**	**Layer thickness**
100 W	7 m/s	25 µm

Table 7: CONCEPT LASER material data sheet.

Metal-ceramic bond strength - 3 point bend test	
Minimum value (ISO 9693)	**Value achievable**
25 N/mm²	40 N/mm²

3.2.2 Evaluation of results

Table 8 shows the results for the metal-ceramic bond strength from the experiment.

Table 8: Bond strength values of the cast, milled, and SLM groups. [27]

Groups	**n**	**Mean +- SD**
Cast	10	32.15 +- 2.39
Milled	10	33.96 +- 4.40
SLM	10	32.31 +- 3.06

All minimum values achieved by bond strength attended the standard ISO 9693, metal-ceramic bond strength 25 N/mm^2 but do not reach an as high number as provided by the manufacturer 40 N/mm^2. In this case, bond strength for CoCr alloys does not depend on the manufacturing method. There are no significant differences among the cast, milled, and SLM CoCr alloys.

Another study, also published last year, performed the same test in porcelain bond strength in 12 samples of CoCr alloys [28]. The results presented from SLM were also in line with Li et al. in [27] presenting even greater values than cast technique respectively: (35.26 ±1.22) for SLM produced parts, and (33.21 ± 3.02) for the cast. One possible reason for the higher bond strength of the SLM group is the surface properties. It can increase bond strength by the creation of undercuts. The surfaces of SLM manufactured components often have sticky powder. This relatively melted powders are added to the surface of components and make them rougher [29]. Due to the inherent roughness of the surface of SLM samples, these surfaces can increase the contact area of framework and porcelain.

3.3 Comparison of outcome results for surface quality and mechanical property made by selective laser melting and traditional technique cast

In his Master thesis, Miah presents an optimization of process parameters for SLM of CoCr powder based on the mechanical part properties [30].
Ten samples made by SLM from CoCr powder are tested without heat treatment and four samples after heat treatment. Heat treatment was performed according to the process of diffusion annealing with normal air and treating process in four steps, according to the material suppliers' recommendation. The tensile test is applied to determine the ultimate tensile strength (UTS). And a predefined set of parameters was set for maximal density. The focus height of the laser beam is varied by changing the parameter beam expander distance. [30]

3.3.1 Collection of manufacturer parameters and values used in the process

Table 9: SLM 100 technical data sheet.

Realizer SLM 100 equipment		
Laser power	**Scan speed**	**Layer thickness**
20 - 200 W	Not provided	20 - 100 μm

Table 10: Parameters used in the process. [30]

Laser power	Scan speed	Layer thickness
Not provided	1.5 m/s	50 μm

3.3.2 Evaluation of results

Tables 11-13 show the results for tensile strength and surface roughness.

Table 11: Average tensile strength between SLM and cast CoCr (ASTM F75). [30]

Average - Ultimate tensile strength	
SLM 100	**Cast**
1056 MPa	655 MPa

Table 12: Process result (SLM 100) of ultimate tensile strength before and after heat treatment. [30]

Average - Ultimate tensile strength	
Before heat-treatment	**After heat-treatment**
1056 MPa	1110 MPa

Table 13: Surface roughness as built (SLM 100) provided by the manufacturer versus research result. [30]

Average - Surface roughness	
Process result	**Manufacturer**
7,56 µm	7 - 9 µm

- The tensile test expresses that specimens made by SLM have almost doubled average tensile strength compared to tradition casting process. The microstructure of SLM built parts differs from the one resulting from a casting process. As the SLM process is a process with repeated re-melting of the produced parts and a high cooling rate, a complex microstructure with fine grains and special phases that influence the mechanical properties.
- There is a small positive influence of heat treatment. After heat treatment, the average tensile strength increased by 5 %.
- Surface roughness Ra attends the values provided by the manufacturer but shows the average result as built: (7.53 µm) not as good as the Ra surface roughness performance achieved as built by the second study: (5.66 µm). Here it can be noticed that the process parameters directly influence the roughness: lower layer thickness and scan speed for smoother results.
- More than 99.80 % of the density of CoCr alloy can be achieved if all the parameters are kept constant [30]. This research density outcome also

complies with values achieved in two other studies: Showing high density acquired by SLM of 99.80 % [1] and 99.94 % [31].

4 CONCLUSION

All the facts presented in this work show the prosperous future of Selective Laser Melting and its high potential for continued development of this technology towards CoCr applications, which do not appear to have been investigated sufficiently to draw definite conclusions about its properties at this time.
In both studies discussing the average surface roughness (Ra), as built samples achieve the values provided by the machine manufacturer. It is also shown, that ultrasonic burnishing post-processing method has a significant good impact on the surface roughness and hardness of additive manufacturing metal components parts. However, no defined specification for surface roughness is a limitation. SLM has limited availability of specified tolerance for frameworks and still faces strong competitors: casting and milling in terms of reliability and time-consuming production.
Furthermore, ultrasonic burnishing of additively produced metals has not been presented to date. One of the reasons could be that it is a slower method compared to traditional machining.
The bond strength in the research results complies with the standard but does not reach the value provided by the manufacturer, showing the manufacturers' tendency to be a little too optimistic. Nevertheless, SLM is showing a promising field for more research and development for dental frameworks. And the ultimate tensile strength research result shows SLM having a better performance than casting. What provides the insight, of SLM eventually replace casting for the production of CoCr frameworks.
The average tensile strength acquired by heat treatment shows a small influence in terms of increasing hardness (5 %). SLM obtains a very dense part, achieving fully (but not 100 %) dense parts. As CoCr is much harder to fabricate using subtractive techniques due to high hardness and low ductility, SLM additive technique potentials to bypass these difficulties.
Therefore, selective laser melting needs a larger number of identical tests to deliver a sufficient database. Quality assurance implies big data management, one of the current bottle-necks in additive manufacturing. It is necessary to carefully work on product development and data preparation, to increase accuracy and repeatability.

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COMPARISON OF FLM AND SLA PROCESSING TECHNOLOGIES TOWARDS MANUFACTURING OF OPTICAL WAVEGUIDES FOR COMMUNICATION AND SENSING APPLICATIONS

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Abstract
Light guiding structures, like optical waveguides or fibers, take an important role in several industries, e.g. communication, sensing, illumination or medical applications. For the latter, it could be very interesting to have the possibility to manufacture problem-adapted structures with a mechanical functionality and with additional embedded optical or electrical sensor functionalities. Modern additive manufacturing (AM) technologies like Stereolithography (SLA) or Fused Layer Modeling (FLM) may provide these opportunities.
This paper is aimed to figure out the light guiding opportunities of both technologies. For this different kind of structures are built by FLM and SLA. To compare both manufacturing technologies, the layout of each structure is identical for both technologies. After manufacturing, the transmission and the attenuation of the guided light of these structures are analyzed by measurement. Then the measurement results of the different technologies are compared with each other.

Keywords:
Additive manufacturing, Embedded optical waveguides, Optical sensors, SLA technology, FLM technology

1 INTRODUCTION

Additive manufacturing (AM) is receiving major media attention and has increased its importance for research and industry. Because of its high flexibility and the ability to manufacture structures that are impossible to produce with conventional manufacturing technologies such as turning, milling or injection molding, it has become an indispensable part of prototyping and is entering the field of direct manufacturing. Additionally, AM enables cost-efficient manufacturing of low quantities with highly individual design features. This makes AM a preferred part of Industry 4.0.
AM is currently entering the field of manufacturing of optical lenses [5]. It is expected that light guiding optical waveguides will be printed directly into structures or can be adapted into such elements [2] after printing.

Seven classes of AM technologies can be differentiated according to current standards. Printing of light-guiding optical structure can be achieved with different AM technologies. This paper is focused on two technologies: Fused Layer Manufacturing (FLM) and Stereolithography (SLA); and their comparison.

The FLM technology enables the application of an expanded variety of materials. In [1], [2] and [3] first results of printing 3D optical waveguides using the FLM processing technology are presented. In these papers, the influence of different core and cladding materials, the length of embedded straight optical waveguides and different waveguide trajectories are analyzed. In [2] a first optical waveguide structure towards optical sensing application is presented. This specimen is based on a symmetrical s-bend structure to analyze the absorption spectra an analyzed material.

The SLA technology is able to manufacture structures with a very small layer size. This enables a high accuracy and a good surface quality of the manufactured optical waveguides.

However, the used SLA printer is not able to manufacture multi-material parts. To properly compare the results of the FLM and the SLA processes, all waveguides are manufactured without cladding material.

2 FUNDAMENTALS OF PRINTED LIGHT-GUIDING STRUCTURES

2.1 Stereolithography

Stereolithography is also known as optical fabrication or resin printing. Figure 1 shows the structure of an SLA system. The printing process is based on liquid plastic resin, which is locally hardened by an UV-laser (Pos. 9). The basis of this process is a photopolymerization reaction, which is initiated by the absorption of UV laser light. The liquid resin (Pos. 7) is stored in a heated tank (Pos. 6) and is distributed after every printed layer by a wiper (Pos. 5). When the level of the resin in the heated tank decreases, it is automatically refilled from a separate tank (Pos. 1). The laser beam works locally and is guided by an X-Y-scanner unit (Pos. 8). To improve the manageability after every print, the object (Pos. 4) is not built directly on the build platform (Pos. 2). An additional support structure (Pos. 3) is required to enable removing the parts from the platform and to ensure that all parts of the object are linked to the build platform. Through this support structure, the printed object can be oriented in almost every direction and rotation.

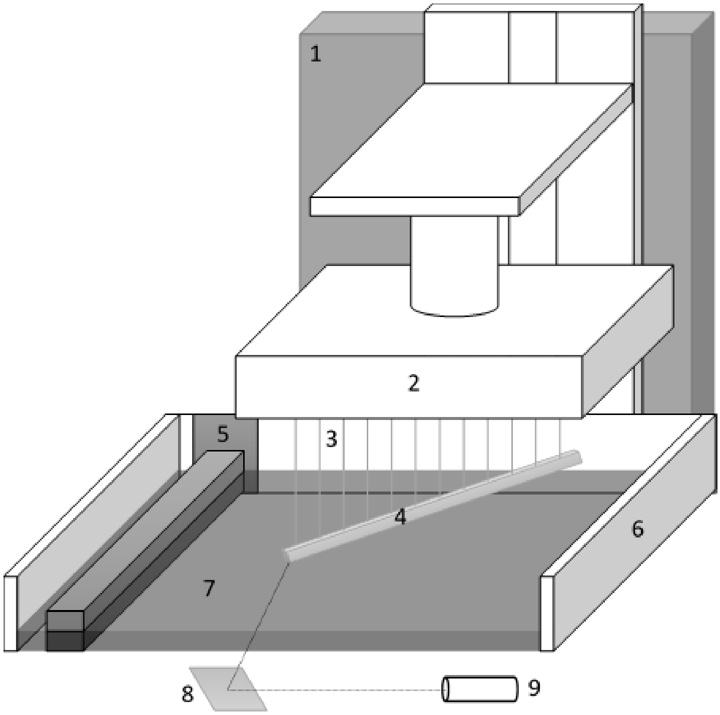

Figure 1: Schematic diagram of an SLA system.

2.2 Optical waveguides

Optical waveguides are used to guide electromagnetic waves of optical frequencies along a trajectory. They are based on optically transparent materials and are manufactured in different forms for various applications, e. g. communication and sensing applications. Every optical waveguide consists of a core and a cladding material. Both materials have an index of refraction *n*, that depends on the relative permittivity ε of each material:

$$n = \sqrt{\varepsilon} \tag{1}$$

To guide an electromagnetic wave by total internal reflection [4], the index of refraction n_c of the core material must be higher than the index of refraction index n_m of the cladding material:

$$\boldsymbol{n_c > n_m} \tag{2}$$

Due to the fact, that the SLA technology is only able to print one single material, air is used as the cladding material:

$$n_m = n_L \approx 1 \qquad (3)$$

When a ray of light hits the interface of two different materials, the ray is split into two parts (Fig. 2). One is reflected at the interface (α_R) and the other one is refracted (α_T). The latter results in a rearrangement of the direction of the ray:

$$\alpha_E = \alpha_R < \alpha_T \qquad (4)$$

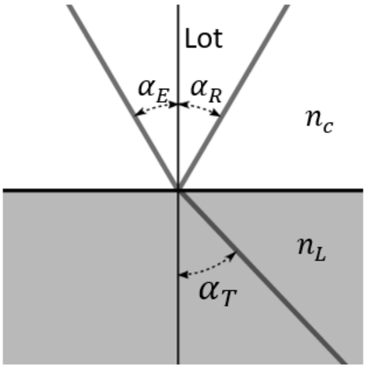

Figure 2: Snell´s law of refraction.

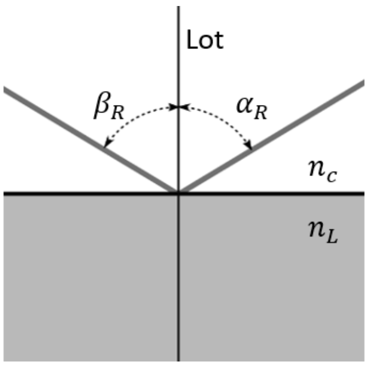

Figure 3: Total internal reflection.

When the angle of incidence is above or equal the angle of total reflection, the light at the interface between two different materials is completely reflected [4], as shown in Figure 3:

$$\alpha_E \geq \beta_R = \sin^{-1}\left(\frac{n_L}{n_c}\right) \qquad (5)$$

Figure 4 shows an optical waveguide. The light ray is coupled into the waveguide and is reflected at the surfaces between the waveguide and the surrounding media. The angle γ must be selected in such a way that the angle α_E is above the angle of total reflection. This is the condition to transmit the entire optical power.

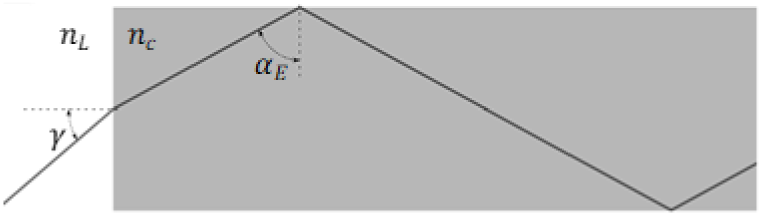

Figure 4: Optical waveguide and the internal reflection of the incident light at the edge of the core.

3 COMPARISON OF OPTICAL WAVEGUIDES PRINTED WITH TWO DIFFERENT TECHNOLOGIES

The SLA printer is not capable of printing two different materials at the same time. To compare the transmission behavior of both technologies, every printed waveguide structure uses air as the cladding material. Additionally, to compare the manufacturing technologies, different structures of waveguides are printed.

To reduce the number of transitions and the eventual attenuation a between two layers, the layers must be oriented along the waveguide in the direction of the light. The layer structures of both technologies are designed as similar as possible to enable the comparison of the transmission behavior. The tool to create the print files for the FLM printer has many options to adjust every parameter of all layers, for example, the layer height, the layer width, and the pattern. SLA print files are created with a different software, which can only vary the height of the layer. The layer structure is defined automatically by the tool.

3.1 Selection of materials

Up to now, the number of materials for the SLA technology is limited. For the applied Formlabs Form 2 only six different materials are available, and only one resin (Clear V4) provides suitable capabilities for optical waveguides. For FLM, an extended variety of materials is available. In [1], polylactic acid (PLA) and polycarbonate (PC) are used to manufacture optical waveguides. In this research, HD glass is used as an additional new material. This is a transparent polyethylene terephthalate with added glycol (PETG).

To compare the attenuation of these materials optical waveguides with outer dimensions of 40 x 3 x 0.6 mm^3 (length x width x height) are printed.

The measurement setup, shown in Figure 5, is nearly the same as in [1]. The laser works at an optical output power of 1.0 mW and with a wavelength of λ = 635 nm. The optical power of the laser (P_e) is coupled into the waveguides by using an optical fiber. The sample is fixed by a holder. The transmitted optical power (P_a) is then measured with a photodiode. To compare the results, the attenuation of all waveguides is then calculated by

$$a = -10\ dB \cdot \log_{10}\left(\frac{P_a}{P_e}\right). \tag{6}$$

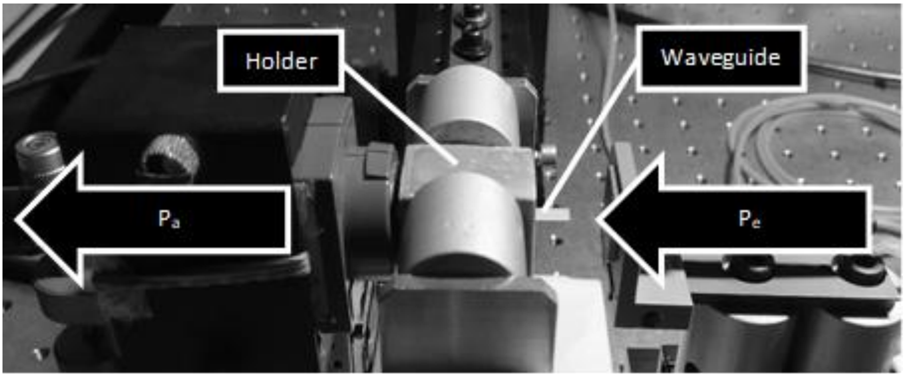

Figure 5: Build-up of the measurement setup.

3.2 Effects by different forms of waveguides

Optical waveguides can be used in many ways. Every application has individual preconditions and needs different types of waveguides. To compare the two printing technologies, two different forms are selected and printed on both printers. The measurement setup and settings are almost the same as in the previous measurements. The interfaces of the waveguides are polished to reduce the attenuation.

Straight structures

The simplest structures of optical waveguides are straight structures. The printed waveguides use a height and width of 4 mm. The length of the structures starts at 20 mm and goes up to 140 mm, increasing by steps of 20 mm. To facilitate good comparisons, all objects are produced with a layer height of 0.1 mm.

As mentioned above, the layer structure of SLA prints is different from FLM prints. Figure 6 shows the layer structure of straight SLA and FLM prints. The layer structure of the FLM technology is the same in the whole object. For the SLA technology, the outermost piece is just like at the FLM technology, but the center part is different. The layers (black) are at a 45° angle towards the outer edge but every second layer (checkered) orthogonal.

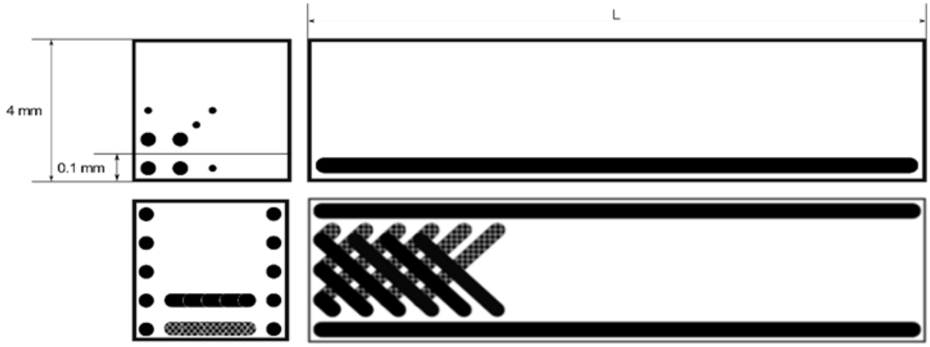

Figure 6: Layer structure of straight FLM prints (top) and SLA prints (bottom).

Curved structures

Curved structures show an important aspect of the light guiding in optical waveguides. A ray of light hits the curved surface and due to the latter, the angle of incidence is different compared to the angle within the straight structure. Due to this, light is coupled into the cladding material and therefore the transmitted optical power decreases. Figure 7 shows the layer structure of both technologies.

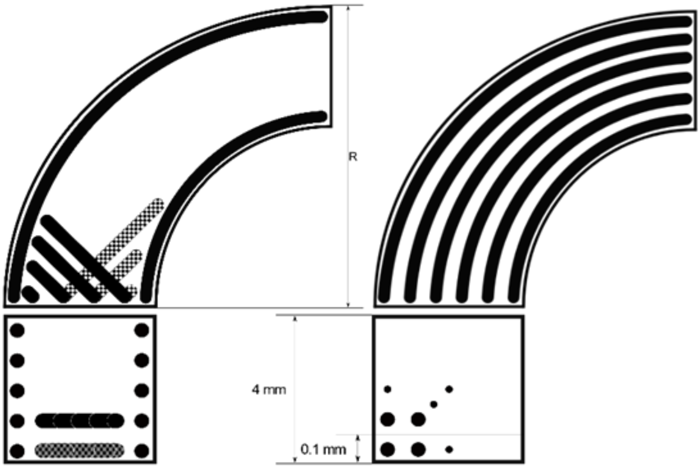

Figure 7: Layer structure of curved SLA prints (left) and FLM prints (right).

The layer structure for the FLM technology is adjusted to the curved form of the waveguide. Every layer is parallel to both edges. The automatically created structure of the SLA technology is the same as in the straight waveguides. The layers are at a 45° angle to the front side.

4 MEASUREMENT RESULTS

During the whole process of design, printing, and measuring, some difficulties have occurred. The most influential one is, that the layer structure of SLA cannot be adjusted manually, and the automatically created structure is not ideal for a waveguide. As an example: At both ends of the waveguides the profile is tapered and the bottom side is not flat. Figure 8 shows one waveguide with both effects.

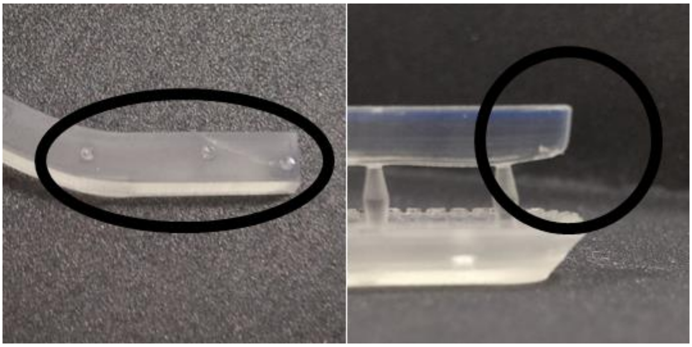

Figure 8: Occurred errors of the SLA-Technology.

During the polishing of the samples another problem occurred: To get a smooth and flat surface, the sample has to be held at a perfect angle without any movement. This is not possible without any tool, which is adjusted to all samples.

4.1 Materials for printing

Both materials, PLA and HD-Glass, are printed in many different settings. The form of the waveguides is similar to the straight waveguides, as described in section 3.1. To compare both, the six best samples of both materials are chosen. Figure 9 shows the attenuation of all samples, arranged from the best to worst.
Because HD-Glass shows a better attenuation than PLA, it is chosen for the comparison of SLA and FLM.

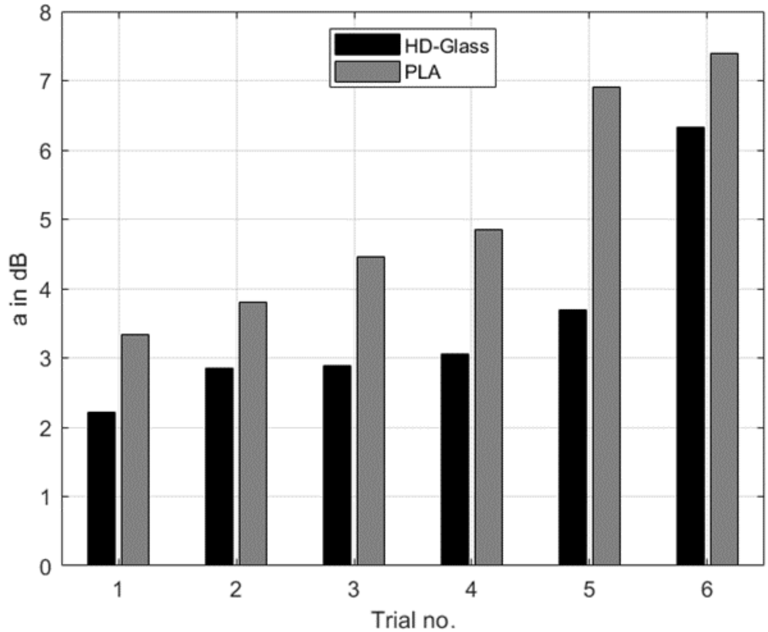

Figure 9: Attenuation of PLA and HD-Glass printed in different settings.

4.2 Attenuation

As stated above, all measurement results were affected by the imperfect surface of the tapered endings of all waveguides. To reduce this effect, the average of all measurements is calculated and displayed. Additionally, to get an overview of the distribution of the measurement results, all measured values are displayed as dots within the figures.

Straight structures

Figure 10 visualizes the attenuation for both technologies and all manufactured waveguide lengths. The SLA waveguides show nearly the expected results. The attenuation is nearly constant by a rising waveguide length.

On the other side, it can be seen, that the attenuation of the waveguides, printed with the FLM technology, is higher than the attenuation of the SLA technology and the attenuation increases with increasing waveguide length. Additionally, all three analyzed FLM waveguides at a length of 60 mm show an unexpected high attenuation. This effect has to be analyzed in a future measurement setup.

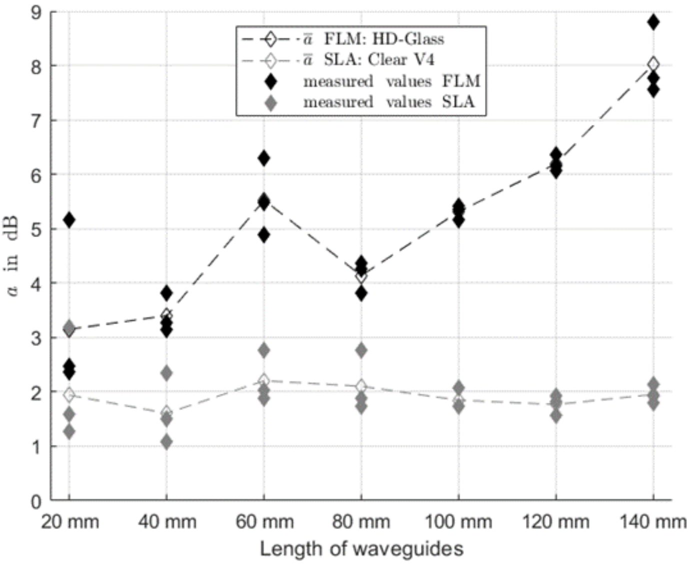

Figure 10: Attenuation of straight waveguides.

Curved structures

Figure 11 shows the results of the measurement of the curved structures. It is visible, that for both technologies the attenuation is increasing with an increasing radius. Probably this is explained by the slant surface and the tapered form of the waveguides (Fig. 8). Due to this, the light can be scattered in different directions and therefore the light is not totally reflected. A longer waveguide causes more reflections and reduces the transmitted optical power.

The attenuation of the curved waveguides is similar to the attenuation of the straight waveguides. It is noticeable that the attenuation of the waveguides, printed with the SLA technology, is reduced with a higher length than 80 mm. The measured values show a high variation and point out that there are further influencing factors that should be investigated in the future.

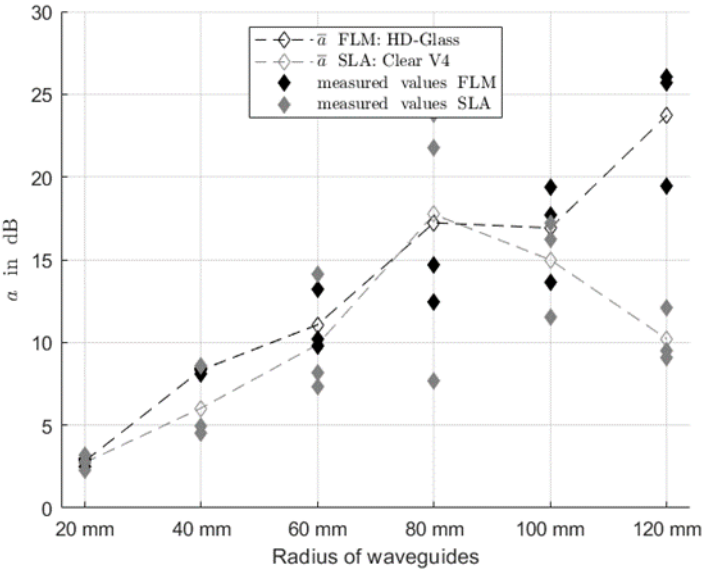

Figure 11: Attenuation of curved waveguides.

5 CONCLUSION AND OUTLOOK

Both technologies are suitable for the manufacturing of straight and curved structures. As a first result, the SLA technology seems to be significantly better suited for printing straight and curved waveguides due to the reduced attenuation compared to the FLM technology. The measurement is affected by some build artifacts, thus, e.g. high attenuation for a single waveguide length or a radius is visible. These artifacts will be addressed in future work.
Due to the current inability to manually create the layer structures of the SLA printer, a major optimizing potential is expected in this field. The use of the new material “HD-Glass” decreases the attenuation of the FLM specimens compared to previous tests. This shows that the FLM technology offers additional potential for improvement.

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SESSION C
Supply Chain Design and Management 1

THE EFFECT OF SUPPLY NETWORK TRANSITION COSTS ON THE INTRODUCTION OF ADDITIVE MANUFACTURING

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Abstract
Additive Manufacturing (AM) is challenging established production technologies. If an established production technology is replaced by AM several other processes are affected, e.g. the supply chain. Well-chosen locations for plants might no longer be the most efficient. Vice versa, the introduction of AM might be less beneficial if plant locations were chosen with different production technologies in mind. There is little research on the effects of introducing AM in the supply chain using quantitative models. A previous paper of us analyzed the effects of AM on supply networks by means of a location-allocation model of a two-stage supply chain together with a comprehensive set of test instances. However, a greenfield approach was assumed. In the present paper, we extend our study and assume existing plants at locations selected with traditional manufacturing technologies in mind. Changing the locations leads to additional transition costs. By means of this enhanced approach, we are able to make more fine-grained analyses and recommendations with respect to efficient plant locations when AM technology is introduced. This also includes the decision, if introducing AM is still reasonable when supply chain effects are considered.

Keywords:
Additive manufacturing, Facility location problem, Supply network structure

1 INTRODUCTION

Additive manufacturing (AM) is challenging to replace established production technologies. Thinking of replacing an established production technology by AM it has to be taken care of the corresponding processes, which are on the interface of the production technology itself. One of them is the supply chain. Since decisions about a production technology assess decisions about plant locations and vice versa [1] it is necessary to evaluate if current plant locations are still effective if AM is introduced.
Though there is a rising interest in research on the impact of AM on the supply chain, investigations often remain on a qualitative level, e.g. [2, 3]. For example, a common understanding is limited to, that supply chains will

decentralize by using AM. In addition, if there is a quantification of the effects of AM, these quantifications are closely linked to individual case studies, e.g. [4, 5], and can hardly be used for more general recommendations.
That is why a more structured and quantitative assessment is required to evaluate if supply chain structures are likely to change using AM. And if so, in which way they will change. In this paper, an existing mathematical model is used and extended for assessing the impact of additive manufacturing on the supply chain structure. The existing model is known as a two-stage capacitated facility location problem (TSCFLP). In a computational study, 525 supply chain structures are considered. Results are analyzed by using seven different logistics-related performance indicators.
In previous research [6-8] a so-called greenfield approach was assumed, i.e., no existing production sites and network structures were considered. This research extends the previous research by integrating transition costs in the model. Transition costs occur if plant locations have to be changed because established production technologies are replaced by AM. Therefore, the enhanced model considers a more realistic situation.
The paper is organized as follows: The basic setup of the computational experiments on supply network structures is introduced in Section 2. In Section 3 the results of our computational experiments are discussed using seven performance indicators that measure the effects of AM on the supply network structure. Section 4 concludes the paper.

2 SET UP OF THE COMPUTATIONAL EXPERIMENTS

In this section, the setup of the computational experiments is presented. First, the basic structure of the supply network is defined. Afterward, the mathematical model for assessing the impact of AM on the supply network is presented. This includes a brief description of the parameters used for the computational experiments. Due to the fact that an existing setup is used the following brief description is based on [6, 8]. For a more detailed description, the interested reader is referred to [6, 8].

2.1 Implications of AM on the supply network

Speaking of additive manufacturing it is not a single technology but an umbrella term for many different technologies. These technologies and therefore AM have one thing in common: AM is ‘‘...a layer-based automated fabrication process for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-depending tools’’ [9]. Due to the different approach of producing parts by adding material instead of e.g. removing material like milling AM has (dis-)advantages compared to established production technologies. A comprehensive comparison is given for example by [4, 10-12]. Among those, there are (dis-)advantages, which could impact the supply chain. For the computational experiments within this paper especially the following are of high interest and are described shortly:

- Functional integration: Using established production technologies usually results in several production steps consisting of producing precursors and their assembly. With AM this is no longer needed. The final part could be produced in one production step [13].
- Higher resource efficiency: If AM is used, only the material which is needed is added to the final product. The unused raw material can be reused in the production of the next part. Therefore less material is required to produce the final part compared to established production technologies [14]. For example, if the part is milled over 80 % of the material is removed from the workpiece [13].
- Especially in the aerospace industry, this effect is described by the term buy to fly ratio. It is the weight ratio of raw material compared to the final product [13].
- Lower production speed: Depending on the part to be produced AM-processes could take more time than established production technologies [8]. This is especially the case if AM is compared to die casting [15].

For further information on how the benefits of AM could impact this model see [6, 8].

2.2 Definition of the supply network

To analyze the impact of AM a stylized two-stage supply network is used. Within this network three different types of nodes are distinguished: sources, production sites, and customers (see Figure 1). The raw material is transported on the first stage of transport from source nodes to production sites. There, a product is manufactured using either AM or established production technologies. On the second stage of transport, the products are transported from the production sites to the customers.

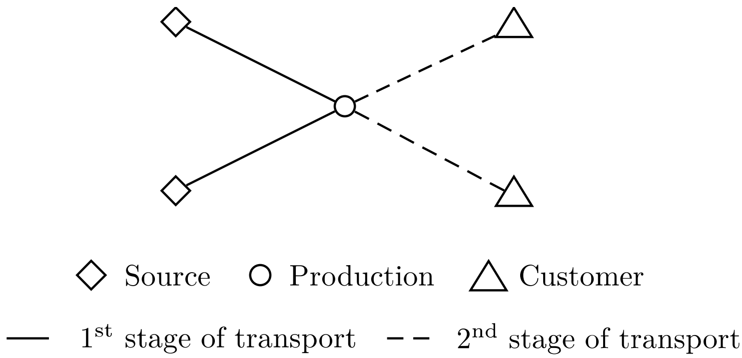

Figure 1: Basic structure of supply network [6].

Since the buy-to-fly-ratio differs depending on the production technology used, the modified buy to fly ratio results in different raw material demand. For example, if a buy-to-fly ratio α of 5 is applied, this results in five units of raw material required to produce one final product.
Because of the functional integration precursors are not considered. The raw material to manufacture a final product is assumed to be homogenous. The quantity of the transported goods (raw material and final products) is quantified in tons. The transport costs are determined by ton-kilometers (tkm). It is the distance in kilometers weighted by the weight of goods to be transported.
A source node can supply multiple production sites. A production site can supply multiple customers. However, the demand of a customer has to be fulfilled by only one production site. Furthermore, storage of raw materials or final products at the production sites is forbidden.
The production sites are restricted in terms of the number of products to be manufactured. Again, this capacity depends on the production technology used. So the buy to fly ratio, as well as the production capacity, are closely linked to the production technology used within this model.
As network design is a rather long-term problem, transport relations between the nodes have no capacities. Furthermore, transport capacities, in particular road transport, are usually easily adaptable.

2.3 Setting up the TSCFLP

For modeling the two-stage supply network described above, the TSCFLP in the formulation presented by Klose and Drexl [16] is used, yet adjusted slightly. In the TSCFLP, a set of nodes N is given. N is divided into a set of source nodes I, a set of potential production sites J, and a set of customer locations K. The TSCFLP is given by (01) to (11).

$$\min z_1 = \sum_{i\in I}\sum_{j\in J} t_{ij}x_{ij} + \sum_{k\in K}\sum_{j\in J} d_k c_{kj} z_{kj} + \sum_{j\in J} f_j y_j + \sum_{j\in J}(1-y_j)\gamma_j \quad (01)$$

$$\text{s. t.} \quad \sum_{j\in J} z_{kj} = 1 \forall k \in K \quad (02)$$

$$\sum_{j\in J} \beta s_j y_j \geq \sum_{k\in K} d_k \forall k \in K \quad (03)$$

$$\sum_{k\in K} d_k z_{kj} \leq \beta s_j s_j y_j \forall j \in J \quad (04)$$

$$\sum_{j\in J} x_{ij} \leq p_i \forall i \in I \quad (05)$$

$$\sum_{j\in J} x_{ij} = \sum_{k\in K} \alpha d_k z_{kj} \ \forall j \in J \quad (06)$$

$$x_{ij} - p_i y_j \leq 0 \forall i \in I, j \in J \quad (07)$$

$$z_{kj} - y_j \leq 0 \forall k \in K, \forall j \in J \quad (08)$$

$$x_{ij} \in \mathbb{N}_0 \ \forall i \in I, j \in J \quad (09)$$

$$y_j \in \{0,1\} \ \forall \ j \in J \quad (10)$$

$$z_{kj} \in \{0,1\} \ \forall k \in K, \forall \ j \in J \quad (11)$$

The capacity of source i and production site j are given by p_i ($i \in I$) and s_j ($j \in J$), respectively. For each customer location $k \in K$ the demand d_k is given. The fixed cost for opening a production site j is defined by f_j ($j \in J$). Costs for

closing an existing production site j are given by γ_j ($j \in J$). By t_{ij} with $i \in I$ and $j \in J$ the transport costs on the first stage of a network are determined. On the second stage of a network, the transport costs per unit from a production site $j \in J$ to a customer location $k \in K$ are given by c_{kj}. The decision variables are x_{ij}, y_j, and z_{kj} ($i \in I, j \in J, k \in K$). x_{ij} indicates the transport volume in tons from source node i to production site j. The binary variable y_j indicates if a production site is used $y_j = 1$ (referred to as open) or not $y_j = 0$. The binary variable z_{jk} indicates if production site j supplies customer location k. The objective function (01) minimizes the total costs that are made up from the transport costs on the first and the second stage of the network plus the costs for opening a new and closing an existing production site, i.e. the transition costs. Constraints (02) ensure that each customer is supplied by exactly one production site. Constraints (03) ensure that the open production sites are able to satisfy the demand of all customers. Constraints (04) guarantee that the capacity of a production site suffices to satisfy the demand of the customers supplied by this production site. The capacity of a source has to be larger than the transport volume of the assigned production sites (05). Restrictions (06) define the flow balance, and the inflow of each production site has to be equal to the outflow. Storage is not possible. Constraints (07) ensure that a source does not supply more raw materials than required by an open production site. Restrictions (08) guarantee that a production site is open if it supplies goods to a customer location. Constraints (09) to (11) define the decision variables.
The formulation of the TSCFLP presented by Klose and Drexl [16] is modified by adding the parameters α in restriction (06), β in restrictions (03) and (04) as well as the transition costs in the objective function (01). The parameter α is denoted as buy-to-fly ratio. It indicates the efficiency of the production process. Low values of α mean a high efficiency. Parameter β indicates a reduced production capacity if AM is used. The transition costs comprise of the parameters fj and γ_j ($j \in J$), which indicate the costs for opening new and closing existing production sites. Within the computational experiments, theses parameters are changed in order to introduce the higher resource efficiency and a reduced production capacity of AM as well as the transition cost of the supply network into the model.

2.4 Input-Data for the TSCFLP

The parameters of the TSCFLP represent the required input data for the experiments. The following parameters were considered:

- The nodes of a supply network, in particular
  - The number of source nodes, production nodes, and customer nodes (allocation) as well as
  - The geographical distribution of these nodes (cluster);
- The buy-to-fly ratio α;
- The production capacity β;
- The transition costs, and

- Some other parameters, whose values were fixed for all instances.

Overall, seven node allocations, twenty-five different geographical distributions and three combinations of the buy-to-fly ratio, production capacities, and transition costs were studied.

Allocation of nodes

There are seven different allocations to be distinguished (see Table 1). The overall number of nodes is set to 90. For a type of node, the number of nodes was set to 10, 20, 30 or 60. For the other types of nodes, the corresponding number was set accordingly.

Table 1: Seven studied allocations of 90 nodes into source, production, and customer nodes [6].

Allocation	*# Sources*	*# Productions*	*# Customers*
A_1	10	20	60
A_2	10	60	20
A_3	20	10	60
A_4	20	60	10
A_5	30	30	30
A_6	60	20	10
A_7	60	10	20

Cluster

Apart from the number of nodes per type of node the geographical distribution of these nodes highly influences the supply network structure. Since an equal distribution of nodes lacks practical relevance in many cases, clusters of nodes are assumed. For each allocation A_i (i=1..7) the nodes were placed randomly and independently of each other on a 100x100 grid using a normal distribution and varying mean and standard deviation.

For all instances, source nodes and customer nodes were placed in one cluster, respectively. Production nodes were located in one cluster as well as two clusters. Mirror or rotational symmetrical clusters are sorted out because these clusters do not represent a unique layout.

Overall twenty-five different clusters are created. Figure 2 shows the different clusters for the three types of nodes. Within this Figure clusters of source nodes, production sites, customer nodes, or no clustering are indicated by S, P, C or Ø, respectively. For a more detailed description on creating the different clusters, it is referred to [6, 8].

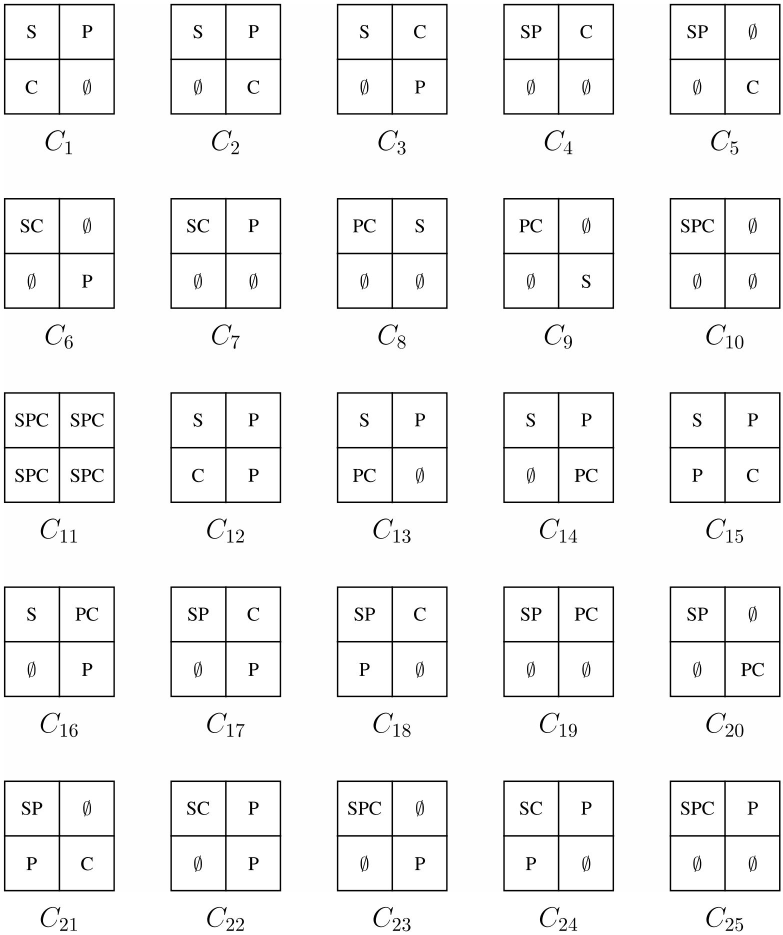

Figure 2: Studied grids with one (C_1–C_{11}) and two (C_{12}–C_{25}) clusters of production nodes [6].

Buy to fly ratio α

The buy to fly ratio indicates the resource efficiency depending on the production technology and therefore influences the amount of raw material transported in the first stage of the transport. According to literature, the buy-to-fly-ratio varies for both, AM [17-19] and established production technologies [19-21]. According to the literature rather moderate values were chosen: α=2 for AM and α=20 for established production technologies.

Variable production capacity β

Producing parts using AM could take more time, than using established production technologies [22-24]. Within these computational experiments, there is now time window defined explicitly. So it is considered constant. With a constant time window, a slower production speed results in a lower production capacity. Therefore, the production capacity is reduced if AM is used. According to [22] β is set to β=1 for established production technologies (α=20) equaling 100 % production capacity as well as a reduced capacity of 55 % (β=0,55) for AM.

Transition costs

The network transition costs are part of the objective function (01). The transition costs comprise of the costs for opening new production sites f_j as well as costs for closing existing production sites γ_j. It is assumed, that the production technology is switched from established production technologies to AM. So for established production technologies (α=20), the optimal network structure is determined in a greenfield approach and transition costs are only included for AM production. Therefore, for α=20 the cost for closing a site γ_j is set to 0, since there are no production sites already opened. The costs f_j for opening a production site $j \in J$ were set to f_j:=5000. This value equals the average tkm for a transport in the supply network from a source node to a customer node.

If AM is used and transition costs are considered the costs for opening new and closing existing production sites is set according to the results of the corresponding α=20-case, i.e.: If a production site $j \in J$ is opened for the α=20-case, the corresponding costs for closing γ_j ($j \in J$) this particular production site is set to 5000 in the α=2 case. Furthermore, the cost for opening this production f_j is set to 0, since it is already opened.

Other input-data

Furthermore, the TSCFLP allows setting different capacities for sources p_i, production sites s_j as well as the demand of customers d_k. For the computational experiments in this paper all of these were set once and are constant for all instances:

- Capacities p_i of each source node $i \in I$ were unlimited, i.e. p_i:=99.999.999 and have therefore no impact.
- Capacities s_j of each production site $j \in J$ were uniform randomly drawn between 100 and 500.
- The demand d_k of each customer $k \in K$ was drawn uniform randomly between 1 and 100.

3 ANALYSIS OF COMPUTATIONAL EXPERIMENTS

In this section, the results of the computational experiments are analyzed. By combining the different allocations and clusters of the nodes as well as the different values for α, β and γ_j overall 525 instances of the TSCFLP are solved by using the mixed-integer programming solver CPLEX 12.6.3 from IBM.

First, the computational experiments for the α=20-case were performed to define the existing production structure. Furthermore, the values for f_j and γ_j for the α=2-case were determined so that the transition costs for switching from established production technologies to AM in a second step. Afterward, the computational experimenters for α =2 (AM) were executed.

3.1 Definition of performance indicators

Similar to [8] the effects of AM on the supply chain structure are measured and discussed by the indicators z_1 to z_6. Additionally, the indicator z_7 is introduced:

- z_1, total cost within the dedicated supply network. z_1 is defined by the TSCFLP' objective function (01).
- $z_2 \coloneqq \frac{1}{|K|}\sum_{j\in J,k\in K} d_k c_{kj} z_{kj}$, the average transport costs per customer on the second stage of the supply network.
- $z_3 \coloneqq z_3^{1st} : z_3^{2nd}$, the proportion of total costs z_3^{1st} arising on the first stage versus costs z_3^{2nd} arising on the second stage of the supply network.
  $$z_3^{1st} \coloneqq \frac{\sum_{i\in I,j\in J} t_{ij}x_{ij}}{\sum_{i\in I,j\in J} t_{ij}x_{ij} + \sum_{j\in J,k\in K} d_k c_{kj} z_{kj}}$$
  $$z_3^{2nd} \coloneqq \frac{\sum_{j\in J,k\in K} d_k c_{kj} z_{kj}}{\sum_{i\in I,j\in J} t_{ij}x_{ij} + \sum_{j\in J,k\in K} d_k c_{kj} z_{kj}}$$
- $z_4 \coloneqq \sum_{j\in J} y_j$, the number of open production sites
- $z_5 \coloneqq \frac{\sum_{j,m\in J;m>j,y_j\neq 0}\sqrt{(\xi_m-\xi_j)^2+(\eta_m-\eta_j)^2}}{\sum_{n=1}^{z_4} n-1}$, the average distance between all production sites used
- $z_6 \coloneqq \frac{1}{|K|}\sum_{i\in I,j\in J,k\in K: x_{ij}\neq 0, z_{kj}\neq 0} t_{ij}+c_{kj}$, the average transport time of one part within the supply network. For this, the distance is transformed in to a general time unit. There, one kilometers equals one time unit.
- $z_7 \coloneqq \sum_{j\in J:\gamma_j\neq 0} y_j$, the number of production sites, which were in use for the α=20-case and are still in use for the dedicated α=2 case.

3.2 Results of computational experiments

It is obvious that the results and analysis of the network structure do only apply to the instances at hand. Other parameters and/or restrictions could lead to results, which could even be contradictory to the results described below.

General Analysis

Table 2 shows the rounded median indicators for the 525 instances. The results are distinguished by the different α. The optimal production network using established production technologies is represented by α=20. For using AM α equals 2. For analyzing the impact of the network transition cost the α=2-cases are distinguished in optimal network structures with and without consideration of the network transition costs (TC).

For z_1 the total costs of the network drop using AM without assessing the network transition costs. If the network transition costs are included the total cost of the network are even lower. Many production sites are reused (see also analysis of z_7 below). Since reusing a production site is free of charge, this results in additional cost savings.

Table 2: Median of the performance indicators with/without transition costs for 525 instances.

Indicator	*buy-to-fly ratio α*		
	α= 2 β=0,55 incl. TC	*α= 2 β=0,55 excl. TC*	*α= 20 β=1*
z_1	44.388	57.046	125.940
z_2	1.190	1.124	1.523
z_3	28:72	32:68	68:32
z_4	5	4	3
z_5	32	31	30
z_6	37	35	44
z_7	3	2	-

Looking at z_2 the average transport cost per customer drop using AM. Since the demand of each customer is constant, a lower z_2 indicates production sites located more closely to the customer. If the transitions costs are included z_2 slightly increases compared to α=2 without transition costs. As mentioned above, more production sites are reused. This results in higher cost savings. But in terms of the average distance between customers and productions reusing production sites could be considered a tradeoff. Reusing existing productions, which are located to fit established production technologies, is less suitable for the network structure if using AM (in terms of distance between production and customer).

With z_3 representing the average cost per stage of transport, the share moves to the second stage of transport. As already mentioned in [6, 8] this might sound contradictive compared to the results for z_2. But z_3 is highly reliant on α. On the first stage of transport, the amount of transported material is ten times lower if using AM. Although lower transport costs on the second stage of transport are realized by an optimized network structure (z_2), the transport cost on the first stage drop way more than the transport on the second stage of transport. So, the share of transport costs on the second stage of transport seems to increase with a lower α.

By including the transition costs the share of transport cost on the second stage of transport is even higher. Lower cost savings could be realized by a changed network structure, because of reused production sites.

The number of production sites opened z_4 increases by one using AM without considering the transition costs. Because of a reduced production capacity for each production site more production sites have to be opened to fulfill the customers' demand. With transition costs included an additional production site is opened.
Concerning z_5 and z_6 the average distance between the production sites used as well as the transport time within the network increases, if parts are produced by AM and transition costs are considered, too. Again this could be considered as a tradeoff accordingly to z_2. That means, by considering transitions cost, the production sites are more distributed within the supply network, yet further away from the customers. By that transport time within the supply network increases.
In addition to [8], z_7 is assessed in this paper. Recall, z_7 indicates the total number of the same productions sites used for the α=20 as well as the α=2 case. There are no numbers given for the α=20-case because z_7 is determined by the outcome of the α=20-case. Without including the transition costs there are already two production sites reused. So there are already production sites reused for AM because they are well located within the supply network. As mentioned before the reuse of existing production sites is free of charge. It suggests itself that the number of reused production sites increases by including the transition costs.
Further insights can be withdrawn if comparing z_4 with z_7: Looking at z_4 for α=20 the number equals the number of z_7 for α=2 with transition cost considered. That means every existing production site used for established production technologies (α=20) remains opened if using AM (α=2) and transition costs considered.

Analysis by allocation and cluster

In addition to the general analysis, the results are analyzed according to their allocation and cluster. The corresponding performance indicators are shown in Table 3. For the Allocation A_3, no performance indicators are provided for α=2. This allocation consists of 10 possible production sites as well as 60 customers to be served. If AM is used, the total production capacity of all 10 available production sites drops below the demand of the 60 customers. Therefore no supply network can be established to fulfill the customers' demand.
By introducing the transition costs the analysis presented above basically applies to the analysis by allocation and cluster as well. The total costs of the supply network drop further (z_1), average distance between production site and customer per customer (z_2) increases, the share of transports cost on the second stage gets higher (z_3), number of productions used rises (z_4), distance between production networks used (z_5) increases, average transport time decreases (z_6) and every production site used at first is reused when AM and transition costs are introduced for almost every allocation and cluster (z_7).

Table 3: Median of performance indicators for different allocations/clusters.

	z_1			z_2			z_3			z_4			z_5			z_6			z_7		
Allocation	α=2 incl. TC	α=2 exkl. TC	α=20	α=2 incl. TC	α=2 exkl. TC	α=20	α=2 incl. TC	α=2 exkl. TC	α=20	α=2 incl. TC	α=2 exkl. TC	α=20	α=2 incl. TC	α=2 exkl. TC	α=20	α=2 incl. TC	α=2 exkl. TC	α=20	α=2 incl. TC	α=2 exkl. TC	α=20
A_1	242.204	288.238	804.947	1.602	1.587	1.830	58:42	56:44	88:12	16	16	10	40	42	32	47	48	48	10	9	
A_2	43.655	54.607	99.175	1.160	1.073	1.503	31:69	35:65	64:36	5	4	3	31	30	31	35	33	41	3	2	
A_3			936.130			1.678			88:12			9			38			50			
A_4	21.186	25.418	38.109	1.329	1.115	1.523	18:82	28:72	41:59	2	2	1	33	31	0	37	34	41	1	1	
A_5	84.314	103.325	176.845	1.464	1.370	2.016	34:66	44:56	66:34	8	7	5	36	32	32	37	34	46	5	3	
A_6	19.226	25.396	39.272	1.112	1.112	1.441	24:76	26:74	55:45	2	2	1	33	39	0	35	34	39	1	1	
A_7	46.065	60.046	102.058	1.375	1.183	1.468	30:70	31:69	61:39	4	4	3	38	34	28	40	40	43	3	2	
Cluster																					
C_1	52.795	67.496	126.811	1.857	1.830	2.058	24:76	25:75	60:40	5	5	3	31	29	23	48	48	55	3	3	
C_2	40.197	55.168	147.584	1.227	1.262	1.582	25:75	27:73	66:34	5	5	4	36	38	29	36	37	41	4	2	
C_3	49.082	60.393	135.349	1.372	1.250	1.678	43:57	48:52	79:21	4	4	3	40	37	34	45	43	52	3	2	
C_4	44.860	55.066	106.879	1.339	1.368	1.881	24:76	25:75	51:49	5	4	3	33	31	29	36	36	48	3	2	
C_5	53.338	61.606	86.717	1.810	1.615	2.567	16:84	23:77	40:60	5	4	3	30	25	29	51	45	61	3	1	
C_6	45.649	56.004	125.940	1.343	1.236	1.906	36:64	36:64	74:26	5	4	3	38	38	30	36	36	46	3	2	
C_7	39.383	49.894	139.886	1.400	1.206	1.478	26:74	29:71	71:29	5	4	3	25	29	27	37	34	45	3	2	
C_8	35.720	47.216	114.555	783	781	1.130	36:64	39:61	71:29	5	4	3	30	30	28	25	27	33	3	2	
C_9	47.223	62.217	143.233	1.138	994	1.440	43:57	48:52	78:22	5	5	3	32	24	28	40	37	44	3	3	
C_{10}	26.138	38.481	54.926	747	688	933	28:72	35:65	61:39	4	4	3	29	33	27	21	21	23	3	2	
C_{11}	33.983	46.463	88.923	880	921	1.277	27:73	35:65	64:36	5	4	3	56	51	50	26	30	35	3	1	
C_{12}	60.325	72.391	192.123	1.892	1.768	2.352	40:60	41:59	60:40	5	4	3	48	40	36	54	53	66	3	2	
C_{13}	43.204	57.321	110.522	1.033	1.011	1.366	33:67	38:62	75:25	5	4	3	41	32	46	37	36	45	3	2	
C_{14}	44.610	58.819	110.227	1.377	1.259	2.104	38:62	46:54	72:28	4	4	3	35	36	30	45	45	56	3	3	
C_{15}	54.938	65.644	98.016	1.589	1.320	2.285	29:71	32:68	66:34	4	4	3	45	45	42	43	40	56	3	2	
C_{16}	38.287	47.522	88.746	896	896	1.069	31:69	33:67	74:26	4	4	2	31	22	43	26	27	34	2	2	
C_{17}	45.488	55.078	75.739	1.322	1.221	1.768	32:68	36:64	50:50	5	4	4	41	42	28	37	37	47	3	2	
C_{18}	48.423	60.746	85.351	1.720	1.516	2.089	18:82	30:70	53:47	5	4	3	30	27	29	44	39	51	3	2	
C_{19}	37.850	51.473	110.321	978	924	1.448	32:68	35:65	66:34	5	4	3	30	26	30	31	29	36	3	2	
C_{20}	56.788	63.797	119.651	1.645	1.342	2.665	26:74	44:56	47:53	4	4	3	41	37	21	49	43	63	3	1	
C_{21}	48.940	57.815	125.952	1.436	1.399	2.458	26:74	29:71	54:46	6	4	4	46	39	32	42	40	62	4	1	
C_{22}	44.613	57.392	129.255	1.113	1.242	1.241	35:65	36:64	78:22	5	5	3	44	38	36	33	34	33	3	3	
C_{23}	28.216	41.031	70.975	874	997	956	29:71	33:67	66:34	5	4	3	38	37	30	23	26	26	3	2	
C_{24}	39.422	51.922	102.058	956	926	1.345	35:65	35:65	72:28	4	4	3	34	34	26	30	30	41	3	2	
C_{25}	29.407	40.687	92.139	775	759	923	36:64	39:61	78:22	5	4	4	27	31	20	23	24	26	3	2	

As observed by [6, 8] the impact of AM on the supply network varies on the allocation and cluster. Especially supply networks, which consist of a high number of production sites to choose from and/or where the concentration of nodes within the grid is high, benefit if AM is introduced. Again, this still applies, if transition costs are considered. But the benefits are smaller due to transitions costs influencing the network structure.
However, a general rule to what extend transition costs impact the supply network can hardly be given. For example cluster C_9 which highly benefits from AM is highly impacted by transition costs, resulting in lower improvements of the performance indicators. On the other hand C_8, similarly to C_9, highly benefits from AM but is barely impacted by transition costs. Same applies for clusters which benefit less from AM.
Summarizing the results of the 525 computational experiments the consideration of the transition costs impacts and changes the supply network structure compared to the previous findings, which did not yet consider the transition costs. With transition costs considered the supply network still improves. But this improvement in the supply network gets limited because of the transition costs. Only the total costs within the network z_1 drop more if transition costs are included. Because reusing existing production sites is free of charge within this model, every existing production site remains in use (z_7). Apart from these two indicators, the remaining indicators change is the same way as already observed by [6, 8] with its greenfield approach. More decentralized networks a built, but especially with z_2 in mind productions sites are located further away from the customers, though.

4 CONCLUSION

Today, AM is considered to complement or even replace established manufacturing processes. A change of the manufacturing technology itself affects other process or organizational structures like today's supply networks. Though there is a rising interest in research on the implications of AM, there is only little research known on the implications of AM on supply chains, especially for research approaches quantifying the implications. In our previous studies, a novel framework on how to measure these potential effects has been introduced. A well-known facility location-allocation problem to model a two-stage supply network has been used and modified. We extended this research by introducing the transition costs of supply network structures. Furthermore, a new performance indicator z_7 was introduced to assess how many existing production sites are still used if AM is introduced into the supply network.
Taking into account transition costs has a big effect on supply network structure: frequently, existing production sites remain open. The main findings of [6, 8] still apply, though. With our assumptions and model, introducing AM in very flexible supply chain environment is much more beneficial than introducing AM in a rigid supply network.

As reusing existing production sites is free of charge in our model, the total costs of the supply network drop even more in comparison with the greenfield approach than if the transition costs are not considered. But the network structure is less efficient in terms of the other performance indicators. Though more decentralized structures are built, the production sites are located further away from the customers because of production sites less suited remain open. Within this paper production processes are compared by applying a high or low resource efficiency and production capacity as well as transition costs in the model. Future research would be to also model further transition effects, e.g. changes in the production program or the customer demand. A supply network with a more generalized network structure than the present two stages would also be a worthwhile area of study.

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PUT-AWAY AND RETRIEVAL OPTIMIZATION STRATEGIES TOWARDS REDUCTION OF BLOCKS RELOCATIONS IN A BLOCK STORAGE

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Abstract

Although it is recommended to store goods in a warehouse based on the principle of first in first out, it is still unavoidable to use block storage of storing, for example, long and bulky goods. If the major advantage of block storage in area saving is the most important, the company has to accept the removal principle of last in first out or in other words, first in last out. The last goods to be stocked are the first goods to be removed and the first stocked goods are the last to be removed.

There are some special observations in the block storage concerned in this paper. The first one is that the goods in the storage ordered by the customers can often not be removed directly from the storage without any stock movement. The aim is to not only benefit from the high-density storage solution but also decrease the negative influence of block storage, especially when pre-stocked goods must be removed at first. The second observation is that during one concerned time period, for example, one day, there may be several operations of put-away and several operations of order picking for shipment preparation. The third observation is that before goods are put away to storage, which goods to be removed are not always predictable. The preplanned removal dates are quite often unexpected changed.

In this paper, scenarios with different dynamic properties and stochastic probabilities have been concerned and defined. Strategies for the three main stages of put-away, i.e. stacking, pre-marshaling and retrieval are defined and examined developed. Simulations have been conducted to examine the strategies based on different scenarios. The aim is to select the right strategy which may reduce the overall relocation operations. It is expected that the sum of blocks movement during put-away i.e. stacking, pre-marshaling, and block retrieval is optimally minimized.

Keywords:

Block storage, Put-away, Blocks relocation, Block retrieval, Order picking, First in last out, First in first out, Pre-marshalling

1 INTRODUCTION

Warehouses are nowadays important facilities at all phases of the supply chain, which aim at storing goods temporarily[1]. The storage technologies used in the warehouse are primarily determined by the products themselves. For example, block storage concerned in this paper is proper for long and heavy goods such as marine containers at container yards, steel plates, steel tubes and so on. All these goods have the generality. They can only be lifted by a crane or another kind of lifting equipment from the top and are named usually as blocks or unit loads.
One block storage in a warehouse is composed of several stacks and can be served by one crane. It is comparable to a bay in the container yard. In each stack, blocks are stacked one above the other to a limited height. The first loaded block can only be lastly retrieved. The last loaded one can be firstly retrieved. Block retrieval means a block is picked up from the top of a stack and removed completely outside of the stack.
The block storage fulfills the first in last out principle. If all the goods stored in the storage have the same properties and can be retrieved without any sequence requirement, it is then very space efficient and economically beneficial to use block storage. However, if the stored goods, above which there are already other blocks to be retrieved, then it is unavoidable to do some relocations of these unit loads in order to access the one to be removed from the storage. That means, for items which require first in first out principle and can only be stored in block storage, it is necessary to relocate some blocks.
One relocation means one block in the storage is moved from the top of one stack to the top of another stack. To accomplish one block retrieval, it may be necessary to finish several block relocations. Hence, the essential problem to be concerned with is how to reduce the relocations for the retrieval of the specified unit loads in the block storage [2]. Figure 1illustrates the blocks to be relocated and the blocks to be retrieved as well. In this figure, three blocks need to be removed from the storage. During the retrieval process, two blocks need to be relocated.

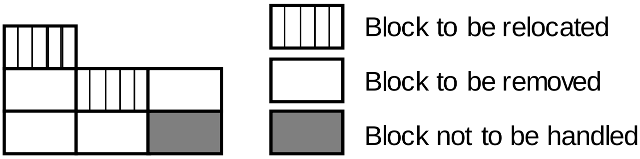

Figure 1: Blocks to be relocated and retrieved.

The handling of blocks can be divided into three phases or stages in the warehouse. They are block put-away or stacking, block storing and block retrieving [3]. It is possible to consider the problem of relocation reduction during the first phase of the storage location assignment for blocks to be stacked. The pre-condition is that the pickup priorities of the blocks are already known. During the storage phase, it is also possible to do pre-marshaling in order to reduce the retrieval operation time. Once the blocks are prepared in the sequence and the target blocks are always accessible without any relocations of blocks for the whole retrieval of the requested blocks or very limited relocations. When the reduction of relocation operations is aimed to be reduced during the retrieval phase, the problem is then the typical blocks relocation problem (BRP). The objective of BRP is to find the move pattern which minimizes the total number of movements required to comply with the retrieval sequence[4]. In the container terminal, the containers relocation problem (CRP) is a typical BRP and has been received a lot of attention. In the remainder of the paper, the term BRP, which is more general, is used as the term for this kind of problems. The methods which are proper for BRP in container terminals are generally also proper for the block storage in warehouses, if the conditions of especially blocks retrieval priorities are the same.
The remainder of the paper is organized as follows. A literature review on optimization problems for block operations in three phases is given in Section 2. The concrete problem which is concerned in the paper is described in Section 3. Section 4 presents the defined strategies and simulation results. The paper is concluded with Section 5.

2 THREE MAIN PROBLEMS IN THREE BLOCK OPERATION STAGES

This section gives a review of the literature in the field of block operations. The main representative methods are selected and briefly presented. According to the three operation stages of stacking blocks, storing blocks and retrieving blocks, the literature concerning the main handling problem at each stage is divided into three parts.
The problem to be handled during the block stacking stage is the storage location assignment. The blocks relocation problem deals with the block retrieval operations during which relocations are carried out. The pre-marshaling happens during the time after the blocks are put away but before they are picked up. The aim is to prepare the blocks in such a sequence so that it is not necessary to do any relocations or very less relocations during retrieval operations. The three types of problems at the three of stages are formulated more or less with the same goal of minimizing the movement of blocks during stacking, pre-marshaling and/or retrieval operations.

2.1 Storage location assignment

Formulas are proposed to estimate the expected number of relocations for retrieving an arbitrary container from a container stack [5, 6]. A dynamic programming model is formulated by Kim et al. [7] to determine the storage location for an arriving individual container to minimize the number of relocation movements expected during loading operations. In their problem formulation, the containers may be assigned three priorities depending on which weight group they belong to. The higher the weight of a container is, the higher the priority of the container has for retrieval. Yang and Kim [8] address both static location problem with known arrival time and dynamic location problem with uncertain arrival time. The static location problem is solved using a genetic algorithm and the dynamic location problem is solved using heuristic rules.

Zhang et al. [9] propose a two-stage heuristic to handle the location assignment for arriving outbound containers even the proportion of the remaining containers on a weight group keeps changing during the container-receiving process. The priority sequence of stacking patterns for each weight group of containers is generated through a neighborhood searching heuristic in the first stage and the incumbent solution is improved by simulating more stack alternatives for each arriving container through a rollout-based heuristic in the second stage.

2.2 Blocks relocation problem

The blocks relocation problem presented by Kim and Hong [2] can be considered as the pioneer formulation of the basic BRP with the following assumptions:

- Only blocks from the top of stacks in the bay can be accessed.
- The relocation of blocks is carried out among stacks in the same bay.
- The relocated blocks can be put only on top of the other stacks. That means no rearrangement of blocks within a stack is allowed.
- No pre-sorting is carried out before retrieval. That means relocations occur only at the moment when blocks are retrieved.
- No block stacking occurs during retrieval operations.
- The pickup precedence of blocks to be retrieved is known in advance and does not change during retrieval operations.
- When a block is retrieved, it is removed from the container bay. Hence, the overall number of blocks in the bay decreases over time.

Obviously, the problem is to minimize the number of moves needed for retrieving some blocks or all of the blocks in the bay with a given retrieval sequence. Figure 2 shows an example of removing blocks with required relocation operations. The boxes simulate the blocks and the numbers inside tell the priorities of retrieving the blocks. Blocks with lower numbers should be removed earlier than the blocks with higher numbers. To remove four blocks in the given sequence 1, 2, 3 and 4, it is necessary to conduct three relocations.

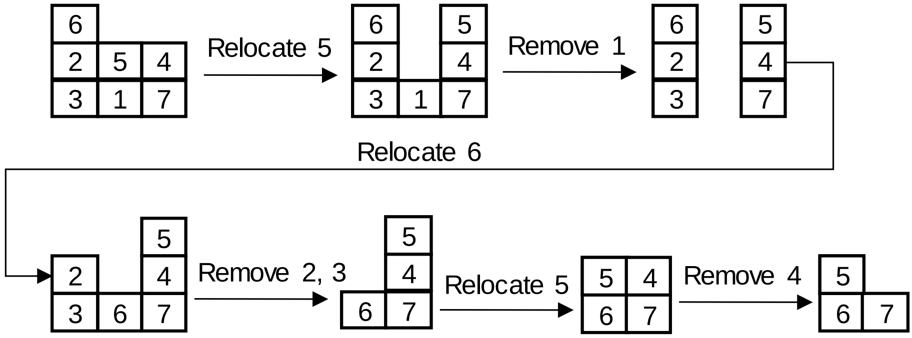

Figure 2: An example of retrieving a set of blocks.

Towards solving this kind of BRP, there are different optimization methods developed in the literature. Caserta et al. [4] utilize dynamic programming formulation in order to solve the BRP by means of the corridor method. In compare to the heuristic addressed by Kim und Hong [2], their method exhibited better results based on the computational experiments. A mathematical model firstly proposed by Caserta et al. [9] encompasses the complete set of features of the BRP. In the three-phase algorithm proposed by Lee and Lee [11], an extended objective combining both numbers of relocation and crane's working time is formulated. In the heuristic approach proposed by Jovanovic and Voss [12], the properties of the block to be moved next are taken into account when the decision where to relocate a block is made. Kim et al. [13] propose a heuristic algorithm for BRP with not only minimizing relocation number but also the working time of the crane.
Galle et al. [14] propose the stochastic model for blocks relocation problem, in which the uncertainty of retrieval time is considered because of the unexpected arriving time of trucks. Zhao and Goodchild [15] examine the influence of completeness of retrieval sequence on container relocation operations. Furthermore, the assumption of no blocks to be stacked during retrieval operations is also questioned.

2.3 Pre-marshalling problem

Container pre-marshaling for container operations can be conducted before retrieval operations start when the blocks are stored in the storage for a certain time. The blocks are pre-sorted in the pickup sequence so that no extra relocations are needed during the retrieval process. Figure 3 shows an example of pre-marshaling of seven existing blocks. For the stock configuration, the blocks are then well prepared after four reshuffling operations for reaching the retrieval sequence without any further relocation requirement.

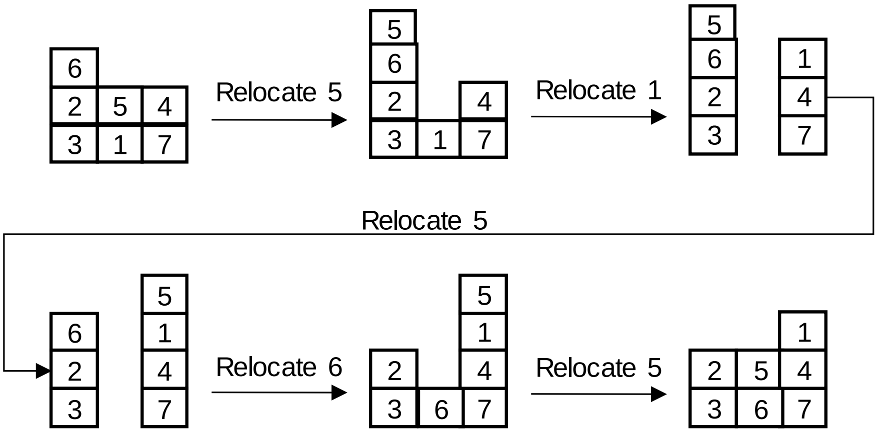

Figure 3: An example of pre-marshaling all existing blocks.

When the two examples in Figure 2 and Figure 3 are compared, it is to notice that from the same initial situation, pre-marshaling needs more relocation operations to reach the final block configuration than doing relocation operations during retrieval. From the viewpoint of relocation reduction, it is not recommended to do pre-marshaling. However, to reduce the retrieval time which determines the loading time of a vessel or the waiting time of trucks, pre-marshaling is then the solution.

Container pre-marshaling problem is often modeled as a mathematical optimization problem with the optimization goal of minimizing the number of container movements during pre-marshaling [16]. Through 37 computational examples, their method is proved to be very effective for solving container re-marshaling problem to prepare the individual containers in a certain sequence or all container groups to be accessible. Lee and Chao [17] develop a heuristic which consists of a neighborhood search process, an integer programming model and three minor subroutines for container pre-marshaling. Izquierdo et al. [18] announce in their paper that they have developed a heuristic for a pre-marshaling problem with better solving quality than the previous ones in the literature.

3 PROBLEM DESCRIPTION

The problem concerned in this paper arises from the warehouse of a block storage for long and heavy goods as blocks, which are handled by an operator manually through a crane. On the one side of the warehouse is the entrance gate and on the other side is the departure gate. There is only one storage place as a buffer at the entrance side. There are ten stacks in the warehouse, each of which has a stacking height of five blocks. 70 % to 80 % of the storage places are normally occupied. Based on the research of Zhao and Goodchild [15], this occupancy grade enables high possibility of economical rehandling of containers for retrieval. The main processes, operations, and available information are described as follows.

At the beginning of every weekday, how many blocks are to be stacked is known. But the exact stacking time of each block is not yet determined. Normally there is one block arriving in the warehouse every one hour to two hours. The operator gets the arriving information of a block round about 30 minutes before it arrives. If one block is placed in the buffer place at the entrance, that means this block can be put away into the warehouse and should be put away in the warehouse before the next block needs the buffer place. The operator can put away the block at entrance immediately once the block arrives or can put it away till the arriving message of next block is received. There is a kind of operation flexibility with a time window from about 30 minutes to 90 minutes.

When the block is to be stacked, the expected departure date of the block may be known, which tells the retrieval priority of the block. The block with earlier departure date is retrieved also earlier. However, even the known departure date may be postponed or preponed. The exact departure time is in most cases unknown. The storage location is just determined by the operator according to the experience and estimation based on the given departure date. If the operator has enough time and the given departure date of the block is known, relocations in limited number may happen. The operator decides then where to relocate the blocks. The aim is not to decline the access sequence of the blocks after stacking new blocks.

On the same day, there are usually several blocks to be removed outside of the warehouse. In most cases, the blocks which have been stored in the warehouse for several days are requested. However, there are also such cases, that some blocks stacked on one day are to be removed on the same day but at a different time.

The same as arriving blocks, it is already known at the day, which blocks in the warehouse are going to leave the warehouse on the next day. But the exact departure time of each block is not given. The departure time of one block becomes clear once the truck arrives at the warehouse. After that, the crane operator does not have much more time to prepare. To access the target blocks, it is quite often necessary to do relocations, which result in waiting time for the trucks. Between two retrieval operations, it may be necessary to accomplish at first the stacking operation.

In order to reduce the waiting time for trucks, pre-marshaling of the requested blocks is usually conducted at the end of a working day. The operator tries to move the blocks especially from the bottom of the stacks to the top of the stacks to increase the accessibility of the block. It is not ensured that every block can be retrieved without any relocations because of the dynamic arriving and retrieval properties of the blocks.

The main problems of the warehouse are the increased wait time for trucks and the overloading of the crane operator. The main concerned question is how to reduce the workload for the operator without influencing retrieval performance or even with better retrieval performance. As a matter of course, the key to answering this question is to reduce the relocation operations along the three coherent stages of stacking, pre-marshaling and retrieving blocks. However, due to problems of information incompleteness, uncertainty and dynamics, it is difficult to develop or apply directly a method for solving the problems arose from three stages simultaneously. The paper aims to find out if it is necessary to use optimization tools for the different stages or not. This aim is achieved through simulations of different strategies for different stages, which are presented in the next section.

4 SOLUTION STRATEGIES AND SIMULATIONS

4.1 Strategy definition

In all seven strategies for all stages in the warehouse are defined. They are numbered from S1 to S7. The first three strategies are used for storage location assignment. The next two strategies S4 and S5 are related to the pre-marshaling operation and the last two are for block retrieval operations. For each stage, one strategy is used.

- Strategy S1: experienced assignment. No location assignment optimization is conducted. The blocks are stacked just randomly or according to the experience of the operator in some stacks with free spaces. And the initial situation is not changed.
- Strategy S2: vertical spread. The initial configuration should be at first through pre-marshaling prepared to a configuration, in which the blocks with the same or close departure data are located in the same stack. After that, the new arriving blocks are also stacked in the stack with the same departure date. Figure 4 shows an example configuration of blocks by using this strategy at the beginning of the second of July. The boxes with question marks inside are those blocks without given departure date. They are stacked in the same stacks.

Tier	1	2	3	4	5	6	7	8	9	10
5	02.07.		02.07.	02.07.			11.07.			
4	06.07.	02.07.	05.07.	03.07.	03.07.	09.07.	10.07.		?	
3	06.07.	06.07.	05.07.	04.07.	03.07.	09.07.	10.07.	12.07.	?	?
2	06.07.	06.07.	05.07.	04.07.	03.07.	09.07.	10.07.	12.07.	?	?
1	06.07.	06.07.	05.07.	04.07.	03.07.	10.07.	10.07.	12.07.	?	?

Stack

Figure 4: Block configuration with strategy S2.

- Strategy S3: horizontal spread. The blocks with the later dates are stored lower in different stacks. The blocks with the same or similar date spread over the whole stacks. That means, in the same stack, the retrieval priorities of the blocks from bottom to top increase. To ensure this, it is quite often to do relocations.
- Strategy S4: experienced pre-marshaling. The preparation of the several blocks on the day for the next day is done according to operator's experience. Because the exact retrieval time is not yet known, all the requested blocks are relocated on the tops of different stacks. That means, above them, there are no other blocks and they are all directly accessible at the beginning of the second day.
- Strategy S5: optimized spread pre-marshaling. The requested blocks are prepared in the same way as strategy 4. That means the final configuration of the requested blocks is the same as the one with strategy 4. The difference is that the relocations are minimized for reaching the same aim of block preparation.
- Strategy S6: experienced retrieval. The same as stacking and pre-marshaling, the operator does the retrieval operations according to experience or randomly.
- Strategy S7: optimized retrieval. For the retrieval operations, the number of blocks relocation for reaching the target block is concerned and minimized.

4.2 Simulations

Data in a time period of four weeks are collected and used as the basis for simulations of the strategy combinations. As shown in Table 1, there are in all twelve strategy combinations, which are numbered from SC1 to SC12.

Table 1: Scenarios of strategy combinations.

Strategy combination	Strategies in stacking stage			Strategies in storing stage		Strategies in retrieval stage	
SC1	S1			S4		S6	
SC2	S1			S4			S7
SC3	S1				S5	S6	
SC4	S1				S5		S7
SC5		S2		S4		S6	
SC6		S2		S4			S7
SC7		S2			S5	S6	
SC8		S2			S5		S7
SC9			S3	S4		S6	
SC10			S3	S4			S7
SC11			S3		S5	S6	
SC12			S3		S5		S7

With respect to stochastic departure date of the blocks during stacking and pre-marshaling, three scenarios are considered. Scenario 1 means that the departure dates of all blocks are known and fixed. There is no uncertainty and incompleteness in the information. Scenario 2 corresponds to the situation with some unknown, delayed and preponed departure dates. Scenario 3 shows an even higher uncertainty in the departure date. The data used for scenario 2 are the historical data being collected. For scenario 1 and scenario 3, data are randomly changed based on the basic data.
A manual analytic approach is used for simulation. That means the relocations during stacking, pre-marshaling, and retrieval are just calculated manually for different scenarios. The simulation results with regard to relocation percentage are shown in Figure 5. The strategy combination SC1 under the scenario 2 corresponds to the current operation situation in the warehouse. We consider the relocation percentage as 100 % for this situation and use this as a benchmark for other strategy combinations. From the results, it is to see that the strategy combination SC8 with Strategies S2, S5 and S7 exhibits the most saving for relocations under three scenarios. The strategy S3 "horizontal spread" for location assignment is in each case not recommended. If the uncertainty of departure dates is higher, the optimization contribution is not any more so obvious.

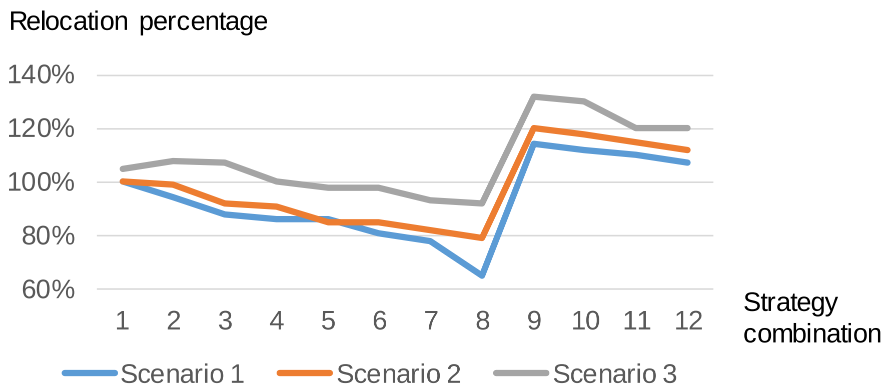

Figure 5: Simulation results.

5 CONCLUSION

In this paper, strategies are defined to reduce the operations, especially the relocation operations for the practical block storage warehouse proper strategy for each stage of block operations is determined based on simulations. The strategies with optimizations contribute in each case to the

reduction of relocation operations when there is more known information on the departure date and the uncertainty of the information is low.
A big limitation of the simulations is the limited time period. Another limitation is that the uncertainty or stochastics of departure dates is only considered in very limited scenarios instead of being generally formulated. The consequence is that the result may be not general enough for other periods anymore. Future work is to develop a software which may adopt the optimization methods from the literature for the blocks operations and enables the automated place assignment.

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SESSION D
Industrial Engineering and Lean Management

DIGITAL LEAN – THE CROSSROADS MODEL FOR CONTROLLING MATERIAL FLOWS IN PRODUCTION AND LOGISTICS SYSTEMS

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Abstract
The complexity and dynamics of production and logistics systems require suitable approaches for controlling material flows in order to achieve corporate goals such as lower costs or faster throughput times. Traditional, mathematical approaches and heuristics reach their limits. An alternative is the control principles of lean production, which are aimed at decentralized, demand-driven self-organization of processes, for example in a kanban control cycle. Production control in advanced manufacturing for smart factories is based on digitally connected entities and sensor technology. Can the approaches be combined – made "lean" through digitalization? Which control approach is the most suitable for steering the material flow? The Crossroads model explains the different approaches and supports the selection of an appropriate method for corporate practice.

Keywords:
Lean management, Smart factory, Digital transformation, Digitalization, Cyber-physical systems, Internet of things

1 MOTIVATION AND OBJECTIVES

"The old one is not finished yet." This is the headline of an article in the German magazine *Der Spiegel* [1]. The article explores the question, "what is new this year?" The same question also applies to approaches for controlling material flows: How can traditional control approaches such as lean – not yet fully implemented in many companies – and the new digital concepts of advanced manufacturing and the smart factory be combined? Companies must increasingly evaluate whether they should continue employing traditional concepts or instead implement new digital approaches. Or is an integration of these two approaches advisable? For these decisions, the Crossroads model provides guidance [2].
First, a basic introduction to lean and advanced manufacturing, or Industry 4.0, is presented. Following the description of the scientific modeling process, an overview of various control approaches is provided, utilizing the Crossroads model as a framework for explanation. Finally, a decision-making model supports the application of the framework in corporate practice.

2 STEERING THE MATERIAL FLOW: LEAN PRINCIPLES VERSUS DIGITAL CONCEPTS

Lean principles hold that more output should be achieved with less input in terms of work, materials, resources, time, and space to better meet customer demands [3, 4]. Continuous flow in the value-creation process and the pull system are regarded as essential elements for the efficient provision of supply in sync with demand. All the processes and activities of an organization must be coordinated and continuously improved in order to maximize value for the customer and eliminate waste in terms of time and resources [4-6]. Lean focuses on the principles of simplification and transfer of responsibility to the human workforce.

Advanced manufacturing, or Industry 4.0, takes a different approach, harnessing the digital transformation of processes, innovative technologies, and IT-supported data analysis. As one commentator summarized, “anything that can be digitalized will be digitalized. And everything that can be connected will also be connected. This affects people, machines and products alike” [7]. In a smart factory, material flows in production and logistics are controlled decentrally, utilizing digitally connected machines, products, components, and employees [8]. Essential elements of a smart factory are networking, automation, and autonomization of processes, as well as integrated decision-making support through assistance systems [9]. Essentially, there are self-controlled processes in which the workpieces carry their production-relevant information with them or on an accompanying workpiece carrier. The information is used to control the workpiece or product autonomously through the value-creation system [10]. Technological pillars of the smart factory are cyber-physical systems and networking of machines, workpieces, and employees via the Internet of Things (IoT). Cyber-physical system (CPS) is a generic term for real, physical objects and processes that are digitalized by means of embedded IT systems and connected to other digitalized, virtual objects and processes [8, 10]. These systems use sensors to register environmental changes and can react independently without interaction with a human operator, so that autonomous, decentralized control and regulation processes can be implemented. The Internet of Things refers to the networking of digitally identifiable physical objects that communicate and exchange data independently via the internet or other networks. This allows a group of several objects such as machines in a production line to perform a process or service independently [11].

Joint objectives of lean and Industry 4.0 are enhancing productivity and establishing self-controlled, decentralized processes [12]. Lean follows the principle of facilitating technology only as a means of increasing customer value and streamlining processes. By contrast, Industry 4.0 focuses on digital technological innovations for networking and process automation in order to implement smart factories with economical production of customer-specific batch size one. Lean is primarily based on simple analog or low tech solutions, such as visual control with traffic light systems, as well as employee creativity

in developing improvements. Industry 4.0, on the other hand, relies on digital technologies and data and therefore accepts the increasing complexity of digitalization and the “dehumanization” of processes.
Porter predicts a new “era of lean” due to digitalization [13]. In particular, the data exchange between the organization and its products at the customer site opens the potential for avoiding waste. For example, maintenance activities can be initiated based on predictive data analytics to reduce downtime. Maintenance is only initiated when the actual demand arises rather than at fixed intervals, which may occur too early and thus encourage waste.

3 STATE OF THE FIELD AND RESEARCH GAP

The few publications on this topic are characterized by a great heterogeneity in terms of research methods, empirical data basis, and the presentation of results. In many cases, only isolated functional areas of the value chain are examined, or statements are limited to a specific industry [14]. The case studies presented do not allow reliable generalization to all companies due to their specific characteristics [15]. The analysis of the impacts of a selected digital technology such as additive manufacturing on lean principles also hardly allows conclusions to be drawn for the questions raised [16]. New terms such as “lean digitization” are being introduced, for example, to present a toolbox of loosely related methods for a lean digitalization of an entire company [17]. The only empirical study conducted concluded that lean processes support the introduction of digital innovations, which in turn offer opportunities for further process optimization [18]. However, the causalities derived on the basis of correlations must be questioned critically, not least because of the limited size of the study and the only marginally presented research methodology.
Information on the interconnections between lean principles and the concepts of Industry 4.0 is lacking. Current literature does not provide a model for explaining and selecting control approaches for production and logistics systems within the tension between “lean versus digitalization.” The Crossroads model closes this research gap.

4 MODELING PROCESS

A model is a systematic description of an object or phenomenon that shares important characteristics with its real-world counterpart. Models are simplified representations of a system. By attempting to reduce the real world to a fundamental set of elements and laws, they support a detailed investigation to gain insights for describing, explaining, forecasting, and designing real systems. Modeling for this study was based on the modeling process proposed by Adam, which has proven successful in numerous application-oriented research projects [19]. Logical and comprehensive model

development was accomplished by the precise definition of five phases with specified results (see Figure 1). The relevant features of the model elements were identified by an analysis of the symptoms of the real-world problem and a subsequent problem formulation. This is the basis for the formulation of the objectives and restrictions for the modeling.
In the present case, the symptom is insecurity of practitioners on how to reconcile lean principles and digital approaches of Industry 4.0. This results primarily from the fact that there is no universal model available for explanation and decision-making on material flow control. Based on these findings, the model is derived, taking into account the major factors for steering material flows in production or logistics system. The Crossroads model serves as a reference model as well as a decision-making model.

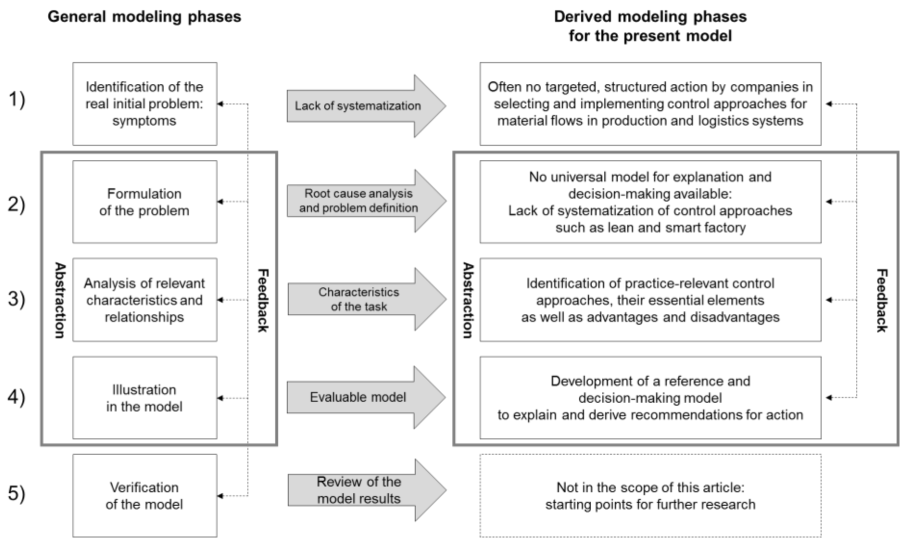


Figure 1: Modeling process (authors' own representation based on [18]).

5 THE CROSSROADS MODEL AS A REFERENCE MODEL TO EXPLAIN CONTROL APPROACHES

Controlling material and information flows serves to achieve business objectives involving costs, inventories, lead times, and flexibility. The complexity and dynamics of a production and logistics system and its environment determines the suitability of a control approach for achieving these objectives. The profitability of the control system, that is, the relationship between the value of the control result and the use of resources, should be ensured.

The Crossroads model focuses on describing, explaining, and designing real production and logistics systems in the area of tension between lean and digital approaches of Industry 4.0 concepts. As a reference model, it structures the perception of the observer and clarifies the essential elements of different control approaches for material flows. The purpose is to analyze and improve a current situation. Since the model has a low degree of specificity, it can be applied to a wide range of industries and value-creation stages.

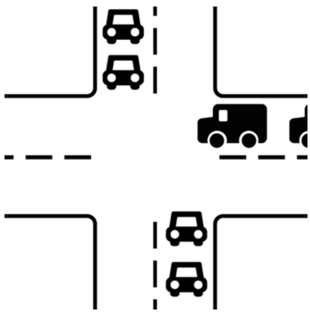
The underlying idea of the model is the traffic control of a road intersection. Typical characteristics of traffic flow and traffic control based on rules and signaling devices such as traffic lights are transferred to the material flow control in a value-creation system. The model's statements on the entity "road user" can be transferred to the entities of the value-creation system, such as components or end products. The analogy to the daily traffic control situation provides a vivid explanation of key characteristics, advantages, and disadvantages of different control approaches.

The model is not limited to control approaches based on lean principles or a smart factory. Due to the historical development of structures and processes in practice, a mixture of different approaches is common; therefore, four control approaches are presented in the following:

I. Static rules, facilitating a centralized technical solution
II. Dynamic rules, utilizing decentralized technical solutions
III. Lean principles for decentralized self-control of entities
IV. "Digital lean": lean principles for decentralized self-control of entities and digitally connected entities and sensors

Figure 2 illustrates an overview of the control system based on heuristics without technical solutions to explain the basic idea of the Crossroads model.

Rules based on simple heuristics without technical solutions



"Right before left" rule
for traffic control

Situation:

- Traffic routes (material flows) "cross" at hubs (intersections)
- Subordinate processes interrupt the main flows according to rules
- Content-wise coupling of network paths via limited capacities per time unit
- Interdependencies with regards to speed and sequence

Undesirable consequences:

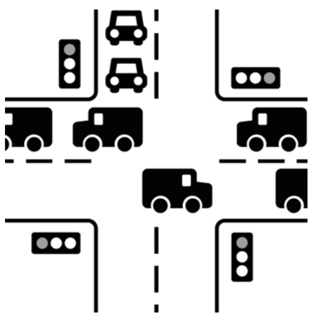
- Inefficiencies due to lack of synchronization: no continuous flow, fluctuating capacity utilization
- Downtimes and waiting times (stocks)
- Potential errors
- Lack of prioritization of orders
- Room for interpretation by employees, possibilities to circumvent rules

Figure 2: Rules based on simple heuristics without harnessing technical solutions.

Figure 3 displays the enforcement of static rules facilitating centrally controlled technical solutions such as traffic lights.

Control Approach I

Static rules, facilitating a centralized technical solution



Traffic light signals steer the traffic flow, based on pre-defined time intervals controlled by a central IT system

Principles:

- Technical solutions for the implementation of simple rules
- Few process variants considered

Advantages:

- No room for interpretation: compliance by employees enforced by signal controls
- Low potential for errors

Disadvantages:

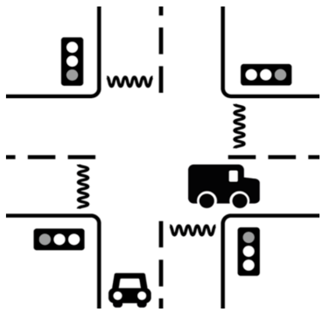
- No dynamic demand orientation, lacking flexibility: traffic light switches based on fixed, pre-defined time intervals
- No continuous flow: fluctuating capacity utilization
- No synchronized flowing in/flowing out of materials: downtimes and waiting times (stocks)
- Waiting periods for clearing the crossroads: buffer times

Figure 3: Static rules, facilitating a centralized technical solution (I).

Control Approach II in Figure 4 displays how control is based on dynamic rules that are implemented utilizing decentralized technical solutions. In contrast to Approach I, the traffic lights control the traffic flow based on demand. Arriving vehicles are identified, facilitating an electromagnetic induction loop under the paving.

Control Approach II

Dynamic rules, utilizing decentralized technical solutions



Demand-driven traffic light signals: vehicle detection using electromagnetic induction loops

Principles:
- Dynamic, demand-oriented control
- Arrival of the entities at the processing stage triggers activity: sensors control actuators

Advantages vs. Approach I:
- Demand orientation, flexibility
- Shorter downtimes and waiting times: reduced stocks

Disadvantages:
- No continuous flow: fluctuating capacity utilization
- Waiting periods for clearance
- Processing sequence suboptimal under certain circumstances: “first-in-first-out” for prioritization does not necessarily result in an optimal solution
- Potential for blockages

Figure 4: Dynamic rules, utilizing decentralized technical solutions (II).

An alternative control approach is based on the lean principles (see Figure 5), which are aimed at decentralized, demand-oriented self-control, for example in a kanban control cycle.
By contrast, the control of material flow in a smart factory is based on digital networks and sensor technology. As with lean, the focus is on decentralized, autonomous self-management, so that the digital, value-stream-oriented management Approach IV is referred to as “digital lean” (see Figure 6).
Combining well-established lean concepts with innovative digital Industry 4.0 approaches can increase customer value and avoid unnecessary time and resources. Due to the digital, real-time networking of research and development (R&D), sourcing, planning, production, and logistics in a smart factory, for instance, short-term, customer-specific requirements can also be taken into account dynamically during production [8].

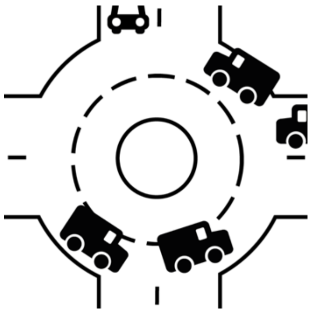
Control Approach III **“Lean”** **Lean principles for** **decentralized self-control of entities**  Roads in the form of a roundabout (instead of a crossroads) without central technical control	**Principles:** • Self-control: the entity decides decentrally and autonomously about flowing in/ flowing out of the system • Dynamic demand orientation **Advantages vs. Approach II:** • Continuous flow • More balanced, higher capacity utilization **Disadvantages:** • Processing sequence suboptimal under certain circumstances • Potential for blockages

Figure 5: Lean principles for decentralized self-control of entities (III).

> **Digital lean** is the ability of a value-creation system to harness digital technologies in a way that increases the maturity of lean principles in value-adding processes. This improves the efficiency both within an individual process and between processes.

Digitalized and networked means of production and workpieces enable real-time monitoring of processes via a digital image in the IT system. Based on this so-called “digital twin,” processes can be planned and controlled on a dynamic level. The digital control of operations in real time offers a high potential for streamlining [17]. It is possible to react quickly to unplanned events such as the failure of a machine, for example, by an independent, automatic adjustment of the material flow taking into account current capacities [8]. The collection of sensor data from a production machine enables predictive maintenance activities to be identified to avoid unplanned downtime and thus wasted resources.
In addition to the possibilities of digital technologies, the creativity of employees and the experience of the “human information system” should be exploited in solving problems and identifying improvements [20]. To achieve this, ad hoc networking of products, machines, and employees via mobile

assistance systems must be ensured. These systems provide employees with context-sensitive information on the status and performance of the value-creation system in order to further optimize processes.

Control Approach IV

"Digital lean":
lean principles for decentralized self-control of entities and digitally connected entities and sensors

Roads in the form of a roundabout (instead of a crossroads).
Digital network of entities.

Principles:
- Self-control: the entity decides decentrally and autonomously about flowing in/flowing out of the system
- Digital networks: synchronization of the entities; for example decentralized, dynamic adjustment of the speed
- Sensors collecting data on, e.g., speed, distance, geo-location
- Creating a continuous flow

Advantages vs. Approaches I, II, III:
- Continuous flow
- Dynamic demand alignment, flexibility
- Consistent, high capacity utilization
- Minimal downtime and waiting times, thus minimized stock levels
- No waiting time for clearing the crossroads
- No blockages

Disadvantages:
- "Fit" to existing solutions
- Level of investment

Figure 6: Digital lean (IV).

6 THE CROSSROADS MODEL AS DECISION-MAKING MODEL FOR DERIVING RECOMMENDATIONS FOR ACTION

How can concrete recommendations for action be derived for business practice? As a normative decision-making model, the Crossroads model structures the selection of a suitable control approach and derives recommendations for action. The framework in Figure 7 enables the decision-maker to systematically grasp the problem. The structure and transparency of the decision field increase the quality of the decision.
A decision-making model represents the assessment yardstick and the decision field. The assessment yardstick comprises the objectives of the decision-maker. Since the decision of a control approach is accompanied by an investment, profitability is chosen as the target figure. Profitability describes the relationship between the value of the result of an action and the consumption of resources. The decision field describes the set of action alternatives and environmental conditions. Action alternatives are the four

control approaches of the Crossroads model. The states of the production or logistics system are mapped as a matrix over the dimensions complexity and dynamics. The dimensions "diversity of product variants" and "lot size" serve to operationalize **complexity**. A distinction is made between "low mix, low volume" and "high mix, high volume." The level of **dynamics** is measured by changes in the product variant mix and output quantity over time. To operationalize the dynamics, the variance coefficient can be used for measuring the predictability of changes. This measure of the relative statistical variation of a product variant's demand is calculated from the ratio of standard deviation and arithmetic mean.
The recommended course of action for a control approach results from the combination of the characteristics of the value-creation system under consideration, described by complexity and dynamics (see Figure 7).

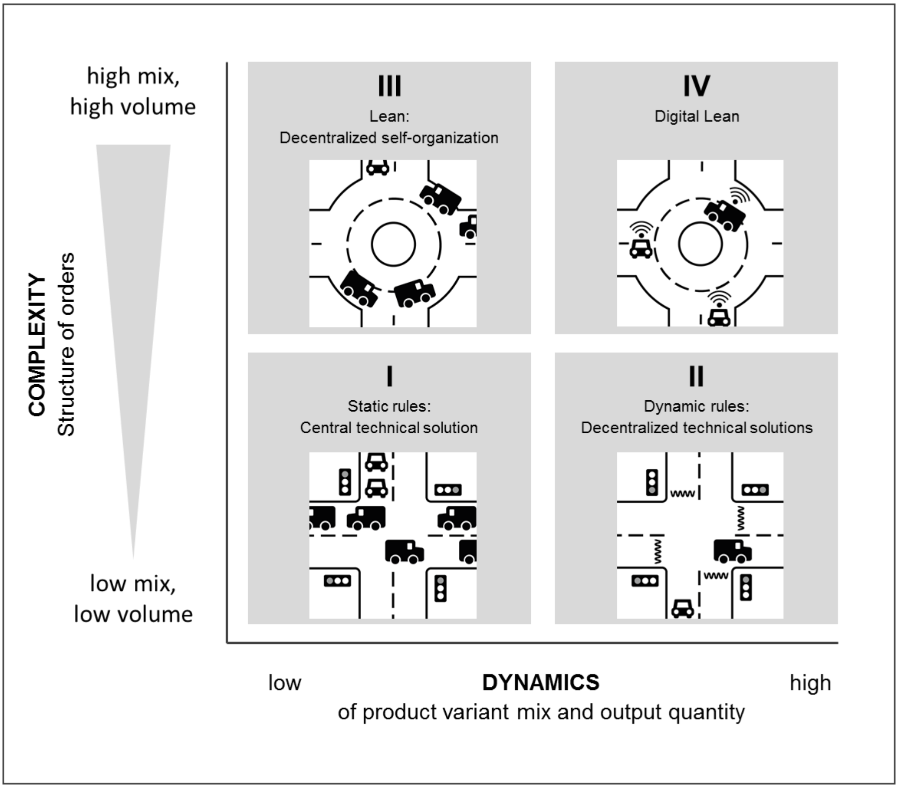


Figure 7: The Crossroads model for deriving recommended actions.

7 CONCLUSION AND OUTLOOK

The Crossroads model explains various approaches for controlling material flows and provides recommendations for action in corporate practice. However, the question is not, “lean or digitalization?” Rather, a solution must be developed to intelligently combine lean and digitization to achieve business goals. The term “digital lean” refers to the ability of a value-creation system to use digital technologies in a manner that increases the maturity of lean principles in business processes. First, the processes should be streamlined based on lean principles. Afterward, the entities of the processes are to be networked with digital technologies in order to leverage further potential for waste reduction, in particular by means of data analysis for continuous process optimization. Technological requirements as a method of achieving process objectives result from dynamic environmental changes such as market requirements. Therefore, this procedure must be repeated periodically in order to iteratively align the technologies currently available with the process requirements.

“The more digital, the better” is not a general rule to follow in the hype of digital transformation. Rather, innovative digital technologies are to be used specifically to further streamline processes. In the value-added process, not only machines and IT but also the human workforce must be connected in an intelligent way.

There are various possibilities for further development of the framework presented here. Gaps in the methods and concepts applied can be closed, and new methods and industry-specific concepts can be added. The model is to be reviewed with regard to its contribution to solving the problem in practice. For the application in a company, the focus can be placed on a specific process area and deepened there. Other target dimensions can be integrated, such as ecological aspects or information costs.

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ASSESSING THE ECONOMIC AND HUMAN-CENTERED POTENTIAL OF ASSEMBLY ASSISTANCE SYSTEMS

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Abstract
Manual assembly workers are usually presented with information on shop floor papers using conventional design elements such as text, tables or drawings. New technological capabilities such as assembly assistance systems can enable more efficient and human-centered delivery of information in manual assembly environments. With this in mind, a method for assessing the economic and human-centered potential of informational assembly assistance systems for a specific work system will be developed.

Keywords:
Complexity evaluation, Manual assembly, Worker assistance system, Work analysis method

1 INITIAL SITUATION AND DESCRIPTION OF PROBLEM

Growing international competition and new technological developments have raised requirements for industrial production [1]. This trend is accompanied by an increase in single-item and low-volume assembly [1]. More and more complex products are being assembled with a large number of variants, either in small batches or custom runs [2]. The unique challenge is to design efficient assembly processes with strong process capability while creating working conditions that motivate and enhance the skills of employees [3]. To meet these requirements, more informational assistance systems must be used in manual assembly operations [3]. These systems assist workers by providing precisely the information they need at the right time so they can quickly utilize and process the information [4].
Despite the economic and human-centered benefits of these systems, which are available on the market, most assembly workers are still provided with information on paper or static on-screen displays [5]. According to a survey conducted by Wiesbeck [6], companies primarily use traditional design elements such as text, tables, or drawings. This type of information delivery can result in human errors [4, 7]. According to studies by Kasselmann and Willeke [8] and Koch et al. [9], the causes of this situation originate from the fact that companies face different challenges in the implementation of these systems. These challenges can be summarized as follows: lack of

implementation strategies, unclear economic benefits and a lack of basic information about systems and providers. There is a special need for research that assesses the benefits and determines the potential applications of assistance systems. The existing methods of Hold et al. [10] or Herder and Aurich [11], which are based on MTM studies, are relatively elaborate to implement. These methods only determine potential applications or requirements for one specific component or assembly process. As a result, MTM studies must examine multiple products/assembly processes in order to determine requirements for a specific work system. Therefore, current methods are inadequate for assessing the potential of assistance systems in existing work systems.

2 OBJECTIVE AND PROCEDURE

The goal of the "Montexas4.0" joint research project funded by the German Ministry of Education and Research (BMBF) (grant no. 02L15A260) is to develop a method with which multiple work systems can be quickly evaluated with regard to their potential economic and human-centered benefits for informational assistance systems. This will allow people, organization and technology to interact in a way that increases efficiency while improving working conditions for employees [3]. The ultimate objective of the method is to compare different work systems on the basis of indicators. The following questions will be answered: "Which work system offers the greatest potential for informational assistance systems and therefore for the change process? How significant is the benefit of the assistance system?" Assumptions, requirements, and objectives have already been defined in the publication by Bendzioch et al. [3]. Two assumptions are made in the publication. First: The worker's need for assistance and the resulting potential benefit of informational assistance systems increases as the task complexity increases. Second: The perceived complexity for the worker depends on the task complexity [12]. In order to measure task complexity as well as perceived complexity, the method must allow for determination of objective indicators and include a survey of assembly system workers using a standardized questionnaire. The goal is to determine a key indicator for the objective as well as the subjective part of the procedure.
The method development process is divided into four steps. The first step consists of the theoretical foundations for developing the method and is based on the article by Bendzioch et al. [3] (Chapter 3). This step focuses on the elements and dimensions that have an impact on perceived complexity and task complexity. Based on this, it is to determine whether existing work analysis methods already meet the requirements of the method to be developed or can at least be partially used. In the second step, a work system of a company participating in the joint research project is analyzed (chapter 4). The analysis focuses primarily on information delivery during the execution of the assembly work. Items and subject areas for the method development

process are determined based on the results of this analysis in combination with the theoretical foundations. A concept for the method to be developed is presented in the third step (chapter 5) based on the previous results (theoretical foundations and case study). In the final step, the developed method is used in the already analyzed work system as part of an initial pre-test (chapter 6).

3 THEORETICAL FOUNDATIONS

3.1 Complexity in assembly operations

Buhr and Klaus [13] define complexity as a characteristic of systems that is determined by the number of elements of the system and the relationships between the elements. The degree of complexity increases with the number of elements and the dependencies between them [13]. In this context, complexity can be described by the characteristics of variety, connectivity, and dynamics [14]. Variety refers to the type and number of elements within a system. Connectivity is the type and number of relations between the elements. The concept of dynamics refers to the unpredictability and indeterminability of system states [14]. Task complexity in assembly operations is therefore dependent on the number and type of system elements, such as the number and type of work items or work equipment, and their interactions with each other. Complexity is also defined by the dynamics of changes, such as new product variants to be produced in the assembly system. The worker, as part of the work system, perceives complexity as the sum of cognitive processes of information acquisition and processing. At the same time, perception is a subjective variable of complexity. Figure 1 shows the drivers and interactions between task complexity and perceived complexity.

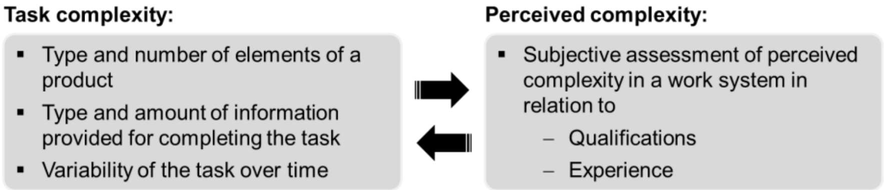

Figure 1: Perceived complexity and task complexity.

The assembly system and workers are subject to constantly changing complexity drivers, which can arise internally or externally. The research project "Supply Chain Integration: Dealing with Complexity" comprehensively examined the complexity drivers within a work system. As part of the research project, workers were interviewed about how they handle complexity. The interviews revealed that complexity is primarily perceived through internal complexity drivers [15]. Examples include process complexity, information complexity, communication complexity, product complexity, etc. [15].

3.2 Work analysis methods

Work analysis methods aim to collect and evaluate information about a specific work system and its employees in order to derive measures based on the analysis results [16]. These procedures are generally focused on identifying the weaknesses and possibilities of a work system design. A variety of analysis methods with different focal points for the different applications has been established over the years. Richter [17] provides a good overview with the "Instruments for Measuring Psychological Stress" toolbox. With regard to "Montexas4.0" project, Gullander et al. [18] offer two methods to capture the complexity of a workstation, the CXI and the CXC method. However, these methods are not aimed at assessing the potential applications of assembly assistance systems. In addition to the CXI and CXC methods, further work analysis methods were selected and compared with the requirements mentioned in the objectives above.

Table 1: Comparison of work analysis methods [3].

	Objective	Subjective	Complexity	Work involved
ISTA	●	○	○	⊙
KOMPASS	●	○	○	○
TBS-S	○	●	○	⊙
RHIA VERA	●	○	○	●
ATAA	●	○	○	●
FAA	●	○	○	●
KABA	●	○	○	⊙
REBA	●	●	○	○
CXI	○	●	●	X
CXC	●	○	●	X

● Applicable; ⊙ Partially applicable; ○ Not applicable, X Insufficient information

Table 1 shows the results of the comparison. Methods are classified as objective and subjective in accordance with Hacker et al. [19], Konrad [20] and Gullander et al. [18]. Objective methods are based on observations or verbal interviews with the job holder, while subjective procedures are based on personal assessments by the job holder [20]. The extent to which a complexity measurement of an assembly system is part of individual methods is assessed based on the objectives of individual methods described by Richter [17] and

Gullander et al. [18]. The amount of work involved in a method is classified based on the data of Richter [17] using the following rating scales: Applicable - four hours or less; partially applicable - more than four and less than eight hours; not applicable - more than eight hours. Table 1 shows that none of the work analysis methods listed fully meet the requirements mentioned above. However, some methods include items or criteria that are relevant to the method being developed here.

4 CASE STUDY OF AN ASSEMBLY SYSTEM

Since none of the work analysis methods studied fully met the requirements, during the joint research project, an assembly system at a mechanical engineering company was analyzed. The analysis included the informational aspects of the work system design. Further items and subject areas relevant for the development of the method will be determined based on the findings and results of this study. In the work system studied, 92 pneumatic products for the assembly line are pre-assembled from 383 different parts. This work is done by one employee and one assistant. The workplace is divided into two assembly areas and features a shelving system with small load carriers containing some of the parts to be assembled. The kanban system is used for supplying materials. Job information is supplied to the worker on shop floor papers that are sorted neither by priority nor by due date. This means that the worker is responsible for organizing the job. Furthermore, it was observed that the workers did not have up-to-date assembly instructions or drawings during the assembly process. Parts were assembled mainly based on experience and sometimes using outdated information. This caused mistakes, confusion of parts, assembly errors, longer walking routes and disruptions of work in order to retrieve information. Times were recorded with classified time steps in order to measure the additional workload caused by the lack of information in the assembly system. This study determined actual times for the assembly of ten components with a total duration of 3 hours and 42 minutes. The results show that 45 % of the total task duration have informational optimization potential [21]. The results also suggest that the examined work system is highly complex. These facts suggest that the examined work system could potentially benefit from the use of an informational assistance system. Further items for improvement can be derived from the results and findings of this study during the method development process.

5 METHOD

Based on the theoretical foundations, the analyzed work system and the publication by Bendzioch et al. [3], an updated method is presented for assessing the potential economic and human benefits of assembly assistance systems. It consists of a standardized questionnaire and a data collection sheet. The questionnaire records the personal experience and therefore the subjective assessments of those working with the assembly system. The questionnaire was designed based on complexity theories, individual work analysis methods (CXI, ISTA, TBS-S, and COMPASS) and the case study from the cooperating company. The questionnaire is divided into six subject areas, as shown in table 2, and comprises 24 items. The closed-ended questions are assessed using a five-point Likert scale. The objective criteria for measuring task complexity are based on the complexity drivers presented and the results of an expert workshop at the company presented. As a result, the following six parameters could be evaluated [3]:

- Number of different parts
- Number of different C parts
- Number of product variants
- Number of tools
- Customer production cycle
- Employee flexibility

Table 2: Overview of questionnaire content [3].

Subject areas	Contents
1. Product	• Product variants • Changes to product and parts • Risk of confusing parts
2. Workflow	• Process descriptions • Tasks to be performed • Job orders
3. Working conditions	• Workplace organization • Processing time • Information delivery
4. Job information	• Cognitive strain • Information processing • Media provided
5. Training & instructions	• Familiarization period • Employee training
6. Frequency of errors	• Assembly errors

The goal of the method is to determine a key indicator for the objective as well as the subjective part of the procedure. For this purpose, the arithmetic mean for the individual subject areas as well as all subject areas is calculated in the subjective part of the procedure. In the objective part of the procedure, the assessment is based on a five-point scale so that a key indicator can similarly be obtained using the arithmetic mean. The two aggregated indicators can be used to determine whether introducing an assembly assistance system in a specific work system is beneficial from an economic and ergonomic perspective.

6 INITIAL RESULTS AND INTERPRETATION OF RESULTS

The developed method was tested in the work system presented above (chapter 4) as part of an initial data collection process. The results of the questionnaire are presented in Table 3.

Table 3: Results of the questionnaire (n = 2).

Subject areas	Average for items per subject area
Product	4.8
Workflow	2.9
Working conditions	2.5
Job information	2
Training & instructions	3.5
Frequency of errors	3

From the point of view of the two employees using the work system, the complexity of the components assembled is 4.8, a very high score. This assessment is caused on the large number of parts and component variants, many of which are very similar to each other. In addition, the task requires frequent retraining because individual components or parts of variants change. The respondents reported average levels of complexity in other areas. The responses with regard to working conditions and job information can be explained by the fact that the two persons have been using this work system for years and therefore do not perceive a high level of complexity. The objective criteria confirm the perceived high level of product complexity. For example, 92 component variants are assembled from 383 different parts in the examined work system (as already mentioned in Chapter 4). Sixty-five tools for assembly are available to the employees in the workplace. On average, nine different variants are assembled per workday in the work system. Overall, the results of the questionnaire (subjective assessments) and the data collection sheet (objective variables) in combination with the work and time studies indicate that an assistance system, if properly designed, can help improve the work situation of the employees as well as the efficiency of the work system.

7 CRITICAL ASSESSMENT AND OUTLOOK

The method presented here describes a possible procedure for assessing the potential benefits of assembly assistance systems. The approach includes the determination of objective metrics and the subjective perception of the employee in order to consider task complexity as well as perceived complexity. Data is collected using a standardized data collection sheet and questionnaire. In this way, the user can quickly evaluate an existing work system with regard to the potential benefits of assembly assistance systems. Further studies will be conducted in order to identify the most important variables for determining the usefulness of an assistance system. The method will then be further developed, for example by adding or modifying items in the questionnaire or data collection sheet. In addition, the questionnaire must be reviewed for compliance with the quality criteria for questionnaire development. In addition, the cluster sizes of the classified objective data must be empirically verified. In the future, it will be necessary to expand on the presented approach to investigate a methodology for selecting and configuring an informational assistance system that meets the requirements. It will also be necessary to investigate how the financial benefits of an assistance system can be evaluated based on the potential applications.

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EMPIRICAL STUDY OF WORKPLACE DESIGN OF MANUAL ASSEMBLY WORKSTATIONS IN SME

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Abstract
Current processes for designing manual assembly workstations do not consider the need for employee-appropriate, product-specific and operating resources-specific factors. A systematic design tool would help to minimize cycle times, increase productivity and improve ergonomic criteria. Therefore, a literature research concerning workplace design for manual assembly was conducted. Additionally, a guided Interview and a questionnaire were developed and approached on the trade show “Motek” with 14 participants. The study shows evidence for the assumption that there is no systematic approach to designing manual assembly workstations.

Keywords:
Manual assembly, Workplace design, Ergonomic workstations, SME

1 INTRODUCTION

Companies in Germany operate in markets which are characterized by takeovers, globalization, and professionalization of low-wage countries [1]. Especially small and medium-sized enterprises (SMEs) have to struggle with this change [1]. Growing competitive pressure in the globalized markets effects that SMEs have to reduce costs at all levels [1]. To stay competitive and moreover to improve sustainability it is necessary for manufacturing companies to optimize their production and processes [2]. Companies’ resources should be pooled in order to reach the highest possible share of added value [3]. To achieve this goal following measures are important [3]:

- Increasing productivity in the production and,
- Designing ergonomic workplaces and ergonomic work procedures.

The assembly is generally the last step of a production process and therefore individual and customized workplaces depend on their products and processes are needed [4]. The change in customer behavior is forcing SMEs to get more flexible and to achieve a higher share in added value processes [4, 5]. In this case, the planning and design of manual assembly workstations become more and more important. The use of conventional manual assembly systems is no longer sufficient [6]. For the implementation of improvement measures, simple assembly solutions have to be developed understandable for each employee especially in SMEs with different operating levels [7]. A systematic planning tool is essential to support SMEs in the challenges of rational planning processes for ergonomic and economic manual assembly design [8].

2 PROBLEM STATEMENT

A detailed view on SMEs illustrates that from an organizational and methodical point of view most companies are not prepared regarding workplace design [9]. The IWT-Produktionscheck®, a tool for measuring the level of work design inside the production process, shows a significant distinction in companies with and without industrial engineering structures [9, 10]. In this context, a market study with 73 SMEs including eight companies with industrial engineering (IE) was carried out [10]. Companies with IE-structures have a higher level of work design [10]. In particular, five factors of the IWT-Produktionscheck® like workplace equipment, tools, production sector design as well as material supply and material withdrawal measure the added value process [9]. The results of the study indicate that SMEs without IE-Department often have a lack in systematic approach regarding optimizing the added value and in picking the best matching design elements.
Furthermore, Reuber [9] determined that SMEs without IE-structures have no or insufficient knowledge respective methods concerning production management and lean production. This was confirmed by Hinrichsen [11]. Also, modular or catalog based design solutions cover individual customer requirements insufficiently [12]. In order to design requirement-oriented workplaces, industrial engineers or employees with comparable qualifications are needed [11].

3 OBJECTIVES AND APPROACH

Based on previous investigations a systematic approach for designing workplaces will be developed. This approach enables the user to follow all necessary guidelines, methods, and factors, to be considered in case of designing manual assembly workplaces. Moreover, SMEs are unable to cover the costs of qualifications and to provide sufficient personal resources for optimizations like industrial engineers [13]. Therefore, it should be examined how SMEs can be empowered to design manual workplaces on their own, especially without external support and additional training.
The vision of this research approach is to develop a methodology, which empowers production-related professionals or supervisors in SMEs, which design manual assembly workplaces independently and swiftly. In addition, the methodology can be implemented in new or renewal projects as a tool for designing manual workplaces.

The basis of this scientific study is a literature review focused on the state of the art regarding manual assembly and workplace design in SMEs. This paper presents an empirical study carried out with external manufacturing experts. The research examined documents actual guidelines as well as existing methods and procedures (chapter 4). Hence, two empirical studies are developed and approached on a trade show “Motek” in Stuttgart. The empiricism of this paper is carried out by using a guided interview and a questionnaire. The aim of this survey is to examine if a systematic approach for designing manual assembly workplaces exists in practice and to assess potentials for improvements of manual assembly workstations in Germany. The survey design is as follows (chapter 5):

1. Guided interview – qualitative insights into the field of design procedures and assessment systems of manual assembly workplaces;
2. Questionnaire – examination of quantitative ratios on the topics of present and future situations of manual assemblies as well as current activities of industrial companies.

Then, the survey data will be compared to the literature (chapter 6). Finally, the results of the interview are used to derive paradigms and requirements for future workplace designs (chapter 7). This analysis provides the basis for production-related executives in SMEs to carry out a systematic workplace design for manual assembly systems.

4 THEORETICAL BACKGROUND

4.1 Manual assembly

The manual assembly is a core element of the added value process [14]. Despite advancing automation, manual assembly workstations in industrial production often cannot be substituted. In particular, varied product ranges combined with small batch sizes as well as complex sensitive assembly operations keep manual assembly as an important manufacturing process in the future as well [15, 16, 17].
Procedures for the planning of assembly systems were developed in the past decades. For example, the six-stage method of REFA [18], a planning systematic of Lotter [19], the approach of Eversheim and Schuh [20], a systematic assembly planning of Westkämper [4] and the simulation-based planning of Feldmann [21]. All literature recommends several steps procedure, which can be carried out manual or IT-supported. Additionally, a variety of laws, DIN standards (i.e. DIN EN ISO 6385) and work scientific recommendations ergonomic aspects [22, 23] have to be considered. Furthermore, the examined literature documents that so far no systematic approach for ergonomic and requirement-oriented assembly workplace design exists. The only exception is presented by Lay [12] who developed an IT-supported visualization of catalog elements. Though a documentation of

the systematic (i.e. what kind of criteria were involved in selecting the items of the workplace) is missing.

4.2 Workplace design in SME

There is an agreement in the literature that workplace design procedures consist of two phases: analysis and design (see Fig. 1) [24]. First, an analysis phase is conducted to collect and evaluate the data concerning the manual assembly workplace product and process (i.e. REFA-workflow-analysis) [24]. Then, the re-, designing phase of the workplace will be implemented and monitored. Attention should be drawn to the fact that the relevant literature deals with the analysis of the process but neglects the design part.

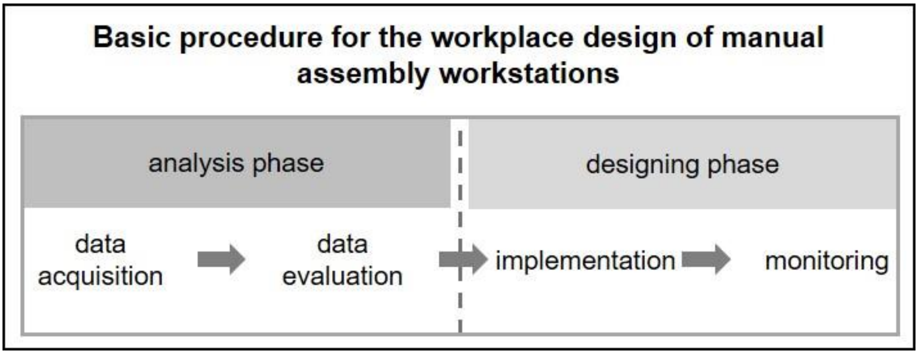

Figure 1: Stage structure to create new or renewed manual assembly workplaces [24].

The need for a systematic design tool for SME is shown in the following case studies:

1. Jungkind et al. [10] examine two manual assembly workplaces in a company producing electrical connectivity technology. To evaluate the work productivity, they used the method REFA-workflow-analysis [25]. Developed and implemented improvement measures of the assembly process effect a decrease of the cycle time of about 36 %.
2. Willnecker [26] comes to similar results. The reorganization of an assembly system affects an increase of productivity by about 20 %. Additionally, ten months after implementation the illness rate of the operators decreased from 9.7 % to 6.2 %. This development is primarily attributed to increasing the value added via workplace design and enhancing the professional qualification to a higher level. Both lead to motivated employees.
3. Reuber and Jungkind [27] confirm the previous findings and quantified the savings regarding an optimized workplace design as an average value of 75,000 EUR per year.

4. Lotter and Hartung [7] conclude that most of the SMEs are not aware that the movement length is an important factor in manual assembly. Simple assembling operations comprise mainly movement length of reach and take. For comparison during a standard operation take the movement length of 20 cm is 47.5 % and at a movement length of 80 cm, it is 70 % of the assembly time.

The previous studies establish via analysis potentials in workplace design but do not consider the whole design procedure including implementation and monitoring. However, Willnecker, Reuber and Jungkind and Lotter and Hartung neglect following questions:

- Which methods, guidelines or laws have to be regarded during the implementation?
- How are the design elements selected?
- What criteria are used to arrange the components and tools?
- Which supply concept has to be chosen (demand- or consumption-orientated)?

The mentioned case studies confirm that workplace design processes are often based on individual expertise and do not follow a systematic standard process. Despite the high importance of manual assembly workplaces, appropriate tools for designing those workplaces are missing. A systematic planning tool, which is custom-tailored to the specific requirements of the situation and the individual qualification level of the planning profession, appears to be the key for professionals or supervisor to

1. Identify potentials in their production processes;
2. Sensitize themselves to downtime in production;
3. Get ergonomic and economic design guidelines for the implementation.

5 EMPIRICAL STUDY

Considering the theoretical findings, a two-step survey is conducted. The first part consists of a standardized questionnaire, which is grouped into two thematic areas and includes twelve items (see Tab. 1). To evaluate the closed items, a four-step Likert-scale concerning the present situation is used as well as a three-step Likert-scale concerning the future situation in 2023 is used. Those items are based on findings in the relevant literature [4, 5, 10] and on results of an expert workshop at the OWL University of Applied Science. The participants of the expert workshop are professors at the OWL University of Applied Science in addition to salesmen and developers of technical factory equipment companies for manual assembly workplaces. The questionnaire surveys the market situation of manual assembly and current fields of action in the production of SMEs. The results are used to identify quantitative ratios regarding potentials for improvement in SME and to point out potential fields of action.

Table 1: Content aspects of the items for the questionnaire.

subject				present situation				importance of future situation in 2023		
				low	rather low	rather high	high	falling	stagnating	rising
1	proportion of assembly workplaces are not automatable in a cost-efficient way		%	o	o	o	o	o	o	o
2	market size	€/a	in pcs.	o	o	o	o	o	o	o
3	lean methods	potential	%	o	o	o	o	o	o	o
4	ergonomics	potential	%	o	o	o	o	o	o	o
5	mental stress	potential	%	o	o	o	o	o	o	o
6	efficiency	potential	%	o	o	o	o	o	o	o
7	quality	potential	%	o	o	o	o	o	o	o
8	industrial engineering	potential	%	o	o	o	o	o	o	o
9	manual assembly assistant systems	potential	%	o	o	o	o	o	o	o
10	share of disadvantageously designed workplaces	SME	%	o	o	o	o	o	o	o
		big enterprises	%	o	o	o	o	o	o	o
11	future role of assembly in Europe			o	o	o	o	o	o	o
12	effort of designing a workplace		h	o	o	o	o	o	o	o

The second part consists of a structured expert interview, which is also grouped into two thematic areas and includes seven key questions (see Fig. 2). The evaluation is conducted by the content analysis of Mayring. Those questions are based on findings in the relevant literature [4, 11, 12] and on results of an expert workshop at the University of Applied Science Ostwestfalen-Lippe as well. The results are used to identify qualitative criteria to survey the assumption that workplaces have no systematic workplace design approach. Furthermore, evaluation criteria should be identified to measure the real improvement of new or renewed manual assembly workplaces.

Actual state of the industry in the …

… design of manual assembly workstations
What are the main steps in the current approach to designing manual assembly workstations?
Which rules and classifications have been taking into account during the configuration?
In which order the design elements are selected?
Are mounting devices or workpiece carriers developed?

… rating system of designed manual assembly workstations
What evaluation criteria of success is measured by the customer?
How user-friendly are the offered products in the configuration? And are the suitable elements chosen by the customer?
How many corrections are made to the customer?

Figure 2: Overview of the key questions of the structured expert interview.

6 RESULTS AND CONCLUSIONS

Within a first survey, the questionnaire and the expert interview is tested. The expert knowledge is based on the practical experience of the respondents, who are currently working for technical factory equipment companies (i.e. Bosch-Rexroth, Item, MayTec). The questionnaires, as well as the expert interviews, were conducted on the 11th and 12th of October 2017 at the trade show Motek in Stuttgart. Fourteen company representatives of technical factory equipment companies for manual assembly workplaces were interviewed.

Essential results of the questionnaire:

- 41 % of the manual assembly workplaces are not automatically a cost-efficient.

- The potential for improvement through workplace design is about 71 % in German SMEs.
- All surveyed companies point out the role of disadvantageously designed workplaces in SME.
- All surveyed companies expect an increasing role of following topics in the manual assembly: mental stress, efficiency, and ergonomics.
- The average amount of time an expert needs to design a manual assembly workplace is about 5.7 hours.

Essential results of the expert interview:
- None of the surveyed companies has a systematic approach to design workplaces.
- The design process as well as their solutions are based on individual expertise and do not follow any systematic standard process.
- The design process usually follows a common concept and neglects employee-appropriate, product-specific and operating resources-specific factors.
- Findings and guidelines in work science research receive little attention
- None of the surveyed companies have criteria to evaluate if the workplace design is successful.
- It is difficult for industrial operators to choose the best matching design elements of a variety of options, in particular of an extensive catalog.

7 DISCUSSION AND FUTURE RESEARCH

A detailed literature research documents that the relevant literature does not include any systematic approach for an ergonomic, economic and requirement-oriented design of assembly workstations. The results of the questionnaire (quantitative ratios) and of the expert interviews (qualitative criteria) combined with the findings of the literature research show evidence for the assumption that a systematic approach for designing manual assembly workplaces would cover the need for employee well-being and efficiency of the work system.

The survey has to be expanded to users of the assembly system, to verify the investigated results and to improve the validity of the methodology. Based on this results a catalog of user requirements should be established. These requirements have to consider research findings (i.e. work science findings, DIN-standards) as well as user-specific criteria (i.e. employees, product, operating materials). For developing a systematic design tool for manual assembly workplaces suitable criteria considering reference modeling have to be chosen. Therefore, the systems can be developed graphically and can be implemented with a relevant software.

A comprehensive evaluation and validation enable the user, more precisely the production-related professionals or supervisors in SMEs, to design manual assembly workplaces swiftly and with regard to ergonomics, efficiency and cycle time. In addition, the methodology can be implemented in new or renewal projects as a tool for designing manual workplaces. At least future research is needed to examine how an evaluation system can be implemented into the systematic design tool to allow a target-actual-comparison.

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HUMAN RESOURCES AND ORGANIZATIONAL DEVELOPMENT IN THE CONTEXT OF INDUSTRY 4.0

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Abstract
In future, advancing digitalization will entail extensive change for businesses. To date, there are only sporadically implemented examples of Smart Factories and these are rather technically (specifically information technology) oriented. Phoenix Contact, therefore, decided to use a tailor-made approach to implement the digital transition towards becoming a Smart Factory. With the participation of the senior management affected, other internal support areas and the works council, an image of the future for the Smart Factory was developed. Based on the main future processes the appropriate organizational structure was selected and all participants could now be trained in the performance of new tasks. In addition, this allows for technological concepts to be chosen and judiciously incorporated in further stages.
In this paper, the "SmartOrg@Combicon" project will be illustrated as the initial phase in the course of Smart Factory implementation.

Keywords:
Industry 4.0, Smart Factory, Digital transformation, Staff and organizational development

1 PROBLEM STATEMENT AND OBJECTIVES

In 2013, the German Federal Government initiated the future-oriented project "Industrie 4.0" (Industry 4.0) because, after mechanization, electrification and computerization, German industry is now on the threshold of the fourth industrial revolution: the arrival of the Internet of Things and the Internet of Services [1]. Primarily, it has to do with the implementation of intelligent and self-organizing factories, also known as Smart Factories [2]. Cyber-physical systems (CPS) serve as the basic technology, which synchronizes physical production processes with digital data in real time [3] [4].
Through Industry 4.0, there will be a major revolution within the areas of technology, internal organization, and personnel, in accordance with the so-called TOP model. The direction and form that development takes are, however, almost impossible to predict [4] [5]. One reason is that the implementation of digitally assisted production processes varies greatly, depending on the relevant business and industry sector [6]. At present, the

development cannot be referred to as a “revolution”, it is, at best a “migration” [4].
For businesses that wish to develop in the direction of Industry 4.0, the problem arises that hardly any detailed and implemented blueprints exist, this applies both to the mission and the transformation process. Therefore, the authors of this paper have thoroughly reviewed the specialist literature, taken part in practice-oriented conferences and visited businesses. It has become evident that the solutions presented are predominantly generic examples, which are mainly related to the theoretical development of production systems with the focus on technological aspects (information and communications technology, automation and microsystems technology); organizational and employee-related aspects appear to have been of secondary importance so far. However, digitalization can only succeed if personnel and organizational issues are considered to be of equal importance to technological and IT solutions [3] as technical adaptability will not limit value creation in the future, rather personnel and operational structures [7].
In this paper is explained how Phoenix Contact developed and partly implemented a digital transformation model for a Smart Factory. Due to the restrictions of this paper, only individual aspects of the method will be described.

2 INITIAL SITUATION AND PROJECT OBJECTIVES

Phoenix Contact GmbH & Co. KG is one of the market leaders and champions of innovation in components, systems, and solutions for electrotechnology, electronics, and automation, with approximately 16,500 employees and production facilities worldwide generating a turnover of around € 2.2 billion. Production shows a high degree of vertical integration and is highly automated. Manufacturing equipment is almost exclusively developed and produced by the in-house mechanical engineering department.
The largest production facility, Combicon in Blomberg, produces printed circuit board (PCB) clamps and circuit connectors. Personnel, both indirect and direct labor, operate in three shifts in the two main production stages: plastic injection molding and assembly.
In 2017, the company management board, due in part to stagnating investment, decided to invest in the move to a Smart Factory model. The main objectives were, amongst other things:

- Implementation of highest service and product quality.
- Increasing efficiency and profitability (on the shop floor as well as management processes).
- Establishing production based on variability and adaptability (operating equipment, personnel and processes).
- Improving the ability to attract qualified personnel.

For this restructuring project, the decision was taken to begin with personnel and organization and to introduce the technological changes afterward. The main focus here was the motto “before we introduce new technology, we train the people and develop the organization”. The following reasons were pivotal to that decision:

- Due to the initially considerable changes to all areas, resistance to change from management and personnel should be identified and addressed, as well as creating the motivation towards active participation.
- In close cooperation with the works council, the company fully recognized the need to discuss any possible negative side-effects with regard to the workforce and to agree on solutions as early as possible.

3 PROJECT PLANNING

The project, as part of the implementation of a Smart Factory, initially focussed on personnel and operations (corresponding to the TOP model), was referred to internally as „SmartOrg@Combicon“. On the basis of the overall objectives for the prospective Smart Factory, a project approach was developed (see Figure 1) using the Balanced Scorecard method [8].

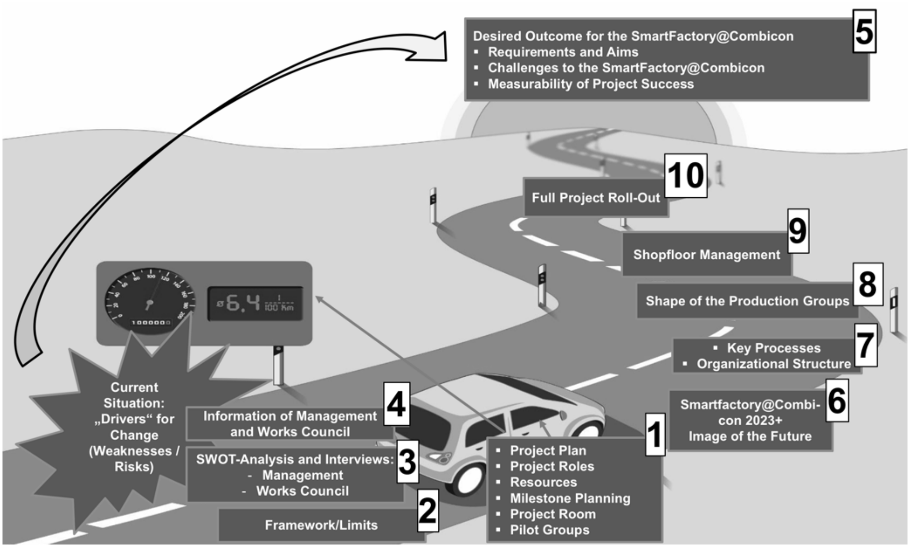

Figure 1: Implementation Procedure for the SmartOrg@Combicon Project.

The client, the project team leadership, project stakeholders and steering committee (including the works council) determined the project structure in a project plan (see phase 1 in Figure 1). The steering committee was comprised of:

- the head of production;
- the heads of both production departments;
- the leaders of the three pilot groups;
- an Industrial Engineering specialist (also project leader);
- the head of Human Resources Management (HRM), also an HRM specialist and
- an external project advisor, from the academic community.

The "SmartOrg" concept would first be tested in three pilot groups, up to phase 9, in order to gain experience and, if necessary, to optimize the process, before the project is rolled out in phase 10. The leaders of the three pilot groups were, therefore, involved in the very early stages of the development process.

A project room served as the communications tool for all parties and as the project team workspace.

Initially, the project framework and limits were determined (see phase 2), these included, for example, measurable efficiency and profitability improvements already achieved by the "SmartOrg" project,

- The development and implementation of a defining organizational structure for a Smart Factory.
- The dependency on support functions (e. g. the central internal mechanical engineering department) should, in future, be kept to a minimum (decentralization).
- The involvement of the core team in the development of a new "working environment" would be of utmost importance (information, communication, involvement), since minimizing fear of change and actively involving employees in the design of their new working conditions is essential.
- Managers prepare their sections for the transition to a learning organization (realize the employee's potential, continuous employee development, offer a clear advancement pathway).

In order to involve them as early as possible, a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) was initially performed [8], with the entire production management team and members of the works council. The focus here was on identifying and prioritizing major weaknesses and risks to production processes integrity arising from the digital transformation. From this, the input data for the concept development was obtained (phase 3), for example:

- to a certain extent, insufficient leadership;
- insufficient transparency and partly interrupted information flow;
- low employee motivation in many areas of production;
- lack of professional, method and soft skills at all levels;

- lack of willingness to change.

With the results from the SWOT analysis, the importance of further training of all participants, creating a new organizational structure, as well as developing a functioning communication structure became evident. Alongside the SWOT analysis, further analyses, for example, time studies of all management in production-related roles, were performed. The results in Figure 2, show that troubleshooting clearly took up most working time, at 27 %, so that far too little time was left for shopfloor management or continuous improvement process (CIP) and self-initiated and controlled projects.
After giving all management and the works council detailed information on the results obtained so far and the further courses of action planned (see stage 4), fundamental “change drivers” were identified (taken from the SWOT analysis and the results of other analyses) and a “Target Situation” was defined.

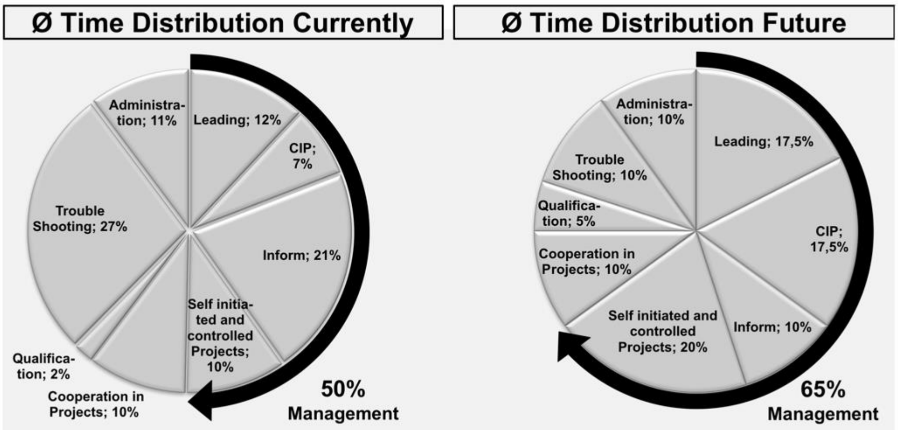

Figure 2: Combicon manufacturing management working time distribution.

Together with the client, on the basis of the general aims for the Smart Factory project listed above, the key objectives for the “SmartOrg” project were defined (see stage 5):

- implement the management and employee profile from Phoenix Contact;
- continuously and proactively update employee skills;
- create innovative capacity;
- implement autonomous managed work groups within the production environment;
- achieve employee satisfaction.

In the following project stage, with the involvement of all team members, a Smart Factory target situation was drafted (see stage 6).
Using the target situation, the most important value chain, support, and management processes were identified and an appropriate organizational structure, including necessary further training, was developed (see stage 7). Due to the significant relevance for the entire project, the new organizational structure will be thoroughly examined later.
Now the shape of all production workgroups could be made (see stage 8). The current project focus is the development of a concept for shopfloor management which, on the one hand, addresses the management and communications problems listed above and, on the other hand, takes the requirements of a Smart Factory into account (see stage 9).
The company-wide rollout of the complete project is planned for the end of 2018 (phase 10).

4 COMBICON SMART FACTORY VISION

The project team was now faced with the question of what form a future Smart Factory would take. There were a great variety of different ideas within the project team. Within the Phoenix Contact group there were selective approaches, however, there was no comprehensive overview. An intense search for how a Smart Factory, with personnel, organization and technology areas could present itself – researching scientific papers, reports from business practice, manufacturer catalogs and internet contributions – did not lead to a satisfactory solution. Consequently, there was no image of the future that could be used as an orientation.
Therefore, the team decided to develop a comprehensive overview of a future Smart Factory. This had a major advantage that all team members could be actively involved, anxieties could be addressed directly and, consequently, the relevant components could be chosen.
A central question whilst developing the image of the future, was where the project team would place the greatest emphasis during the Smart Factory development process. One of the main points was to decide between a technically centered automation and one centered on staff organization of tasks. In specialist literature, these conflicting demands are also framed as a question: is it going to be a technically oriented automation scenario, in which the Internet of Things steers the staff, or a staff-centered tool scenario, in which the employees steer the Internet of Things [9] [10]. Prioritizing one of these scenarios over the other also determines the future organizational structure. Although Phoenix Contact, as a technology-driven business, will automate more and more systems, the team, after intensive discussion of both scenarios, were unanimous of the opinion that it would remain a staff-centered tool scenario, with people as the foremost decision-making body [11]. An autonomous Factory 4.0 was not considered to be feasible in the near future; people would still perform a central role in order to secure flexibility and

productivity [11]. The control of standard, routine activities would be given over to CPS, complex and experienced-based decision making would continue to be made by people; in addition, CPS components capable of operating in real-time could be used [11]. Staff in production, particularly the mid and low skilled, are then left with a greater latitude in decision making compared to a technically oriented scenario. Demands on employees would, however, be more varied and greater due to intervention when a malfunction occurs, or process optimization needed because they will have to manage more and take more decisions [4] [10].
In addition, this scenario is equal to process-oriented task organization, in which decision making is decentralized and greater responsibility must be adopted by all levels of management, this is accompanied by increased competency requirements [4].
During several workshops, the project team successively developed an image of the future. For this purpose, the available source material was reviewed, contacts from university research facilities used, and input from specialist departments in the Phoenix Contact Group (Mechanical Engineering, Human Resources Management, IT etc.) was obtained.
After approximately three months and internal coordination, the image of the future “Smart Factory Combicon 2023+” could be approved. The image of the future was drawn up according to the process structure shown in Figure 3, oriented towards the customer and their requirements, which were supplied by the value chain. The supplier services the value chain and, keeping service-orientation in mind, digital and physical support processes and management process follow. The lower half of Figure 3 shows further support activities or topics.

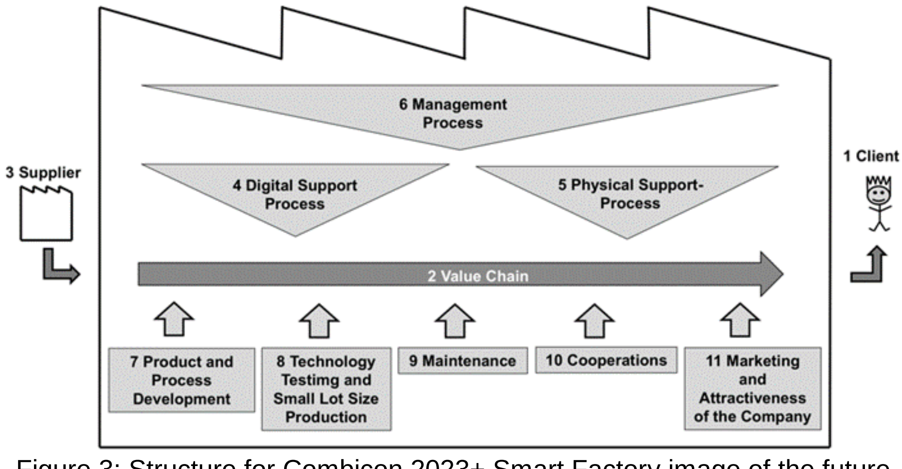

Figure 3: Structure for Combicon 2023+ Smart Factory image of the future structure.

Figure 4 shows a detail of the final image of the future. For the key range of topics illustrated in Figure 3, descriptions in the form of storyboards were created, with which a uniform vocabulary and understanding of the scene could be ensured; moreover, that a common language would be spoken and understood within the framework of further internal and external Combicon production communication.
The existence of an image of the future served not only as a basis for communication but also an orientation for the new organizational structure and the necessary adjustments associated therewith.

Figure 4: Smart Factory Combicon 2023+ image of the future (detail).

5 ORGANIZATIONAL STRUCTURE

On the basis of the analyses undertaken and the image of the future, the various Smart Factory Combicon organizational structure models could now be developed and assessed.
The result was an organization with 10 production groups (formerly “workshops”), which had a similar layout to the current one. Figure 5 shows the new management structure of a production group with between 30 and 50 employees over three shifts. In comparison to the present organizational structure, the span of control is considerably reduced and significantly more professional skills and controlling competence are integrated into the production groups, in order to implement the process orientation and the level of self-direction contained in the image of the future. The function of the production group leader during the transformation will be first to shape his

team and facilitate the development of employees towards to their job descriptions. As coordinator between the various specialist functions, the priority will then be to develop the interfaces between the organizational structure, in order to drive innovation with established technical excellence and CIP. The production group leader is assigned a representative, the production coordinator, who should primarily assist with training the team in technology. A process optimizer is an optional position intended for the execution of projects and the development of processes; the complexity of this position diminishes as processes become established. The production controller will, as system support improves in the future, mainly drive digital process development. To improve management and communication, shift leaders will take over the specialist coordination of employees during each shift: they will be the daily business contact person. Skilled labor employees, as experts in their production processes, will then be required to gain digital knowledge and assume more responsibility than they have at present. Other unskilled employees will also be required to assume more responsibility and they will have to be trained to work more independently within the teams, in order to collectively guarantee production continuity, especially when a malfunction occurs. Finally, an optional process assistant is envisaged, who supports the teams with regard to quality, efficient task organization, and supply of materials. The functions of this role will, however, increasingly diminish with the increasing automation and digitalization.
Figure 5 also shows that, in contrast to the current organizational structure, manufacturing engineering will be integrated into departments in future, to ensure technical competence and, therefore, independence from central departments. Furthermore, a Lean Management role will be integrated into the teams, in order to drive organizational and employee-related innovation, in cooperation with Human Resources.

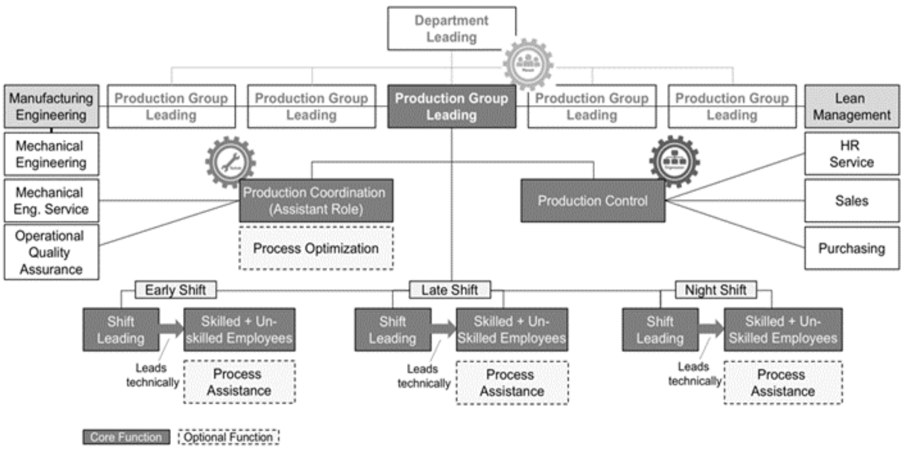

Figure 5: Desired organizational structure of Smart Factory Combicon.

On the basis of the desired organizational structure, the functions defined therein and the Smart Factory Combicon 2023+ image of the future, specific job descriptions were developed. Using qualification matrices, a timeline could now be used to develop and implement specific measures to increases production employee qualifications.
At the same time, on the basis of the current situation outlined above and the image of the future, over a timeline between 2018 and 2023, specific steps necessary for the "SmartOrg@Combicon" project could be identified, for example, a standard shift handover, autonomous employee work scheduling or the implementation of dashboards. These steps were allotted to one pilot group, tested, optimized and then implemented by all three pilot groups.
All of the measures are chronological and consistent, displayed for all to see in the project room and their implementation is monitored. In this way, training needs can be geared towards the implementation of other necessary steps.

6 SHOP FLOOR MANAGEMENT

Shopfloor Management (SFM) is a very important project phase. The project team was clear that it goes far beyond the illustration and discussion of performance figures and performance boards.
SFM is rather the CIP motor. Through SFM, management excellence shall be gradually developed in Combicon production [9].
In the project presented here, it is a matter of:

- Develop vertical integration within production areas, at present a hierarchical thinking still dominates, foremost amongst the specialist and the lower skilled employees.
- Ensure manager presence on the shop floor to enable managers to be aware of each of their employees and to use their strengths individually [12].
- Improve information flow during shift handovers and
- Implement CIP measures rapidly.

Initially, SFM is intended primarily for the production team leaders, as this is felt to have the greatest need for action.
The project team decidedly described

- their specific management responsibilities,
- management tools, such as structured daily schedules, A3 approach, or escalation levels, as well as
- the desired leadership behavior.

However, SFM should be implemented from all levels of management down to on-site employees. A detailed description of further project steps/phases is not considered to be necessary here.

6 CONCLUSION

During the project presented here, it became clear to all participants that genuine and early participation in the implementation of a Smart Factory is vital. Future management has had a decisive influence on the method, as well as the project phases. This takes time: for this project, it has taken approximately one year to get to the shop floor management stage. But it pays off, all team members, especially the management who were involved, are now Smart Factory evangelizers and communicate the concept enthusiastically to their staff and other management.
On top of this, the participants in this process, with its many uncertainties, develop their competencies and learn how to identify challenges, to prioritize them and find solutions during the project stages. In this way, the operating managers have, over the last quarter, successively taken responsibility for implementation and further project stage development and are now confident drivers of the whole project.

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SESSION E
Wood Processing Technologies and Furniture Production

GEOMETRIC TOLERANCING OF FURNITURE

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Abstract
DIN 68100 has been worked out in the 80s to provide for the furniture industry a frame to tolerance lengths but since the last rework also angles, parallelism, and straightness. It includes a method to take swelling and shrinkage of wood and wood-based materials into account. Apart from its benefit of specifying products in a supply chain, it is rarely used in the branch nowadays.
In 2011, the system of Geometrical Product Specification (GPS) has been published completely. The system is built for a distinct range of geometrical quality characteristics and consists of chains of standards referring to each other. With three elements of these chains, the product can be specified. With three additional elements, the verification of the product and the measuring system is possible. It does not contain the verification of the production processes.
DIN 68100 with its current contents is far away from GPS and must be reworked in the near future. New symbols for drafts and an updated method to tolerance with moisture consideration have to be developed so that the standard might be integrated into the GPS system. Due to a shift in the tolerance principles, the GPS system is hardly directly applicable to the furniture industry. But there is a real threat that the system is called up accidentally and out of ignorance.
This paper tries to sketch a comprehensive system of product specification and verification for the furniture industry. It will share experience gained in the kitchen industry and will add a theoretical analysis of a possible application of GPS-chains for important examples of quality characteristics.
The activities are part of a process (VDI 3415-2) carried out in the working group 102 of the Society of German Engineers (VDI). In the past, similar activities of this group have been reported at the PEM Conference.

Keywords:
Geometrical Product Specification (GPS), Tolerances, Specification and verification, Furniture

1 INTRODUCTION

The globalization is continuing. Sub-suppliers deliver their products from all over the world to the OEM, also in the wood and furniture branch. A precise specification of the needed part is a condition precedent to avoid

misunderstandings and reclamations. The branch emerged out of traditional roots and has its own style of defining a product or workpiece. Besides that the “Tegernseer Gebräuche” for machined wood are the oldest written usance in Germany, the traditional rules are not up to date. To include diverse sub-suppliers in an interchangeable manufacturing line, fitting tolerances are needed. DIN 68100 provides a standard for general tolerances including a method for taking differential shrinkage and swelling into account, one of the major issues the branch is struggling with. The other important issue is the surface quality of furniture parts. The appearance is so dominating that functional surface characteristics like roughness are simply not sufficient to describe the desired quality. VDI 3414 tries to define quality characteristics and shows a way to evaluate them. State of the art is the definition and specification by a complete and consistent drawing. DIN 919 is the standard for technical drafts of the furniture branch and gives some specific symbols for typical problems.
All mentioned standards, DIN 68100, DIN 919 and VDI 3414, do not comply with the system of specification and verification constituted in the Geometrical Product Specification (GPS), published and valid since 2011.

2 GPS SYSTEM

2.1 History

The committee ISO-TC 213 / CEN/TC 290 has been working on these items since the 90s of the last century. Hundreds of standards were reworked according to a master plan, later called Matrix [1] and set consistently in relation to other standards in the same field. The aim of the work was and still is to assure a higher level of functionality, functional assurance and interchangeable manufacturing of the specified workpieces.

2.2 GPS Masterplan, GPS Matrix, GPS Chain

The masterplan (ISO 14638) combines different standards on the same field to chains. The chain elements are defined for certain usage-related topics for the specification (first three elements) or verification (last three elements):

- Chain link A: symbols and indications (examples see Figure 1);
- Chain link B: feature requirements;
- Chain link C: feature properties;
- Chain link D: conformance and non-conformance;
- Chain link E: measurement;
- Chain link F: measurement equipment;
- Chain link G: calibration.

Combined from the geometrical features:

- Size;
- Distance;
- Form;

- Orientation;
- Location;
- Run-out;
- Profile surface texture;
- Areal surface texture and
- Surface imperfections.

A matrix is created and is later used in newer releases of the ISO committee.

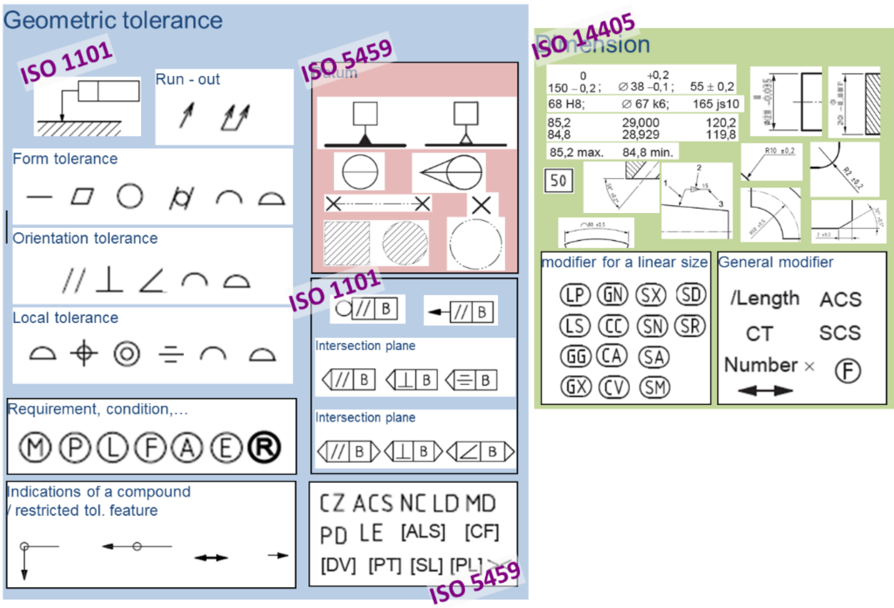

Figure 1: Overview of the ISO GPS standard [http://www.asd-ssg.org/pmi-interoperability].

The principles of the GPS system is defined by rules in ISO 8015; ISO 14638 provides an additional explanation (Figure 2). The fundamental principles are [2]:

- Invocation principle;
- Principle of GPS standard hierarchy;
- Definitive drawing principle;
- Feature principle;
- Independency principle;
- Decimal principle;
- Default principle;
- Reference condition principle;

- Rigid workpiece principle;
- Duality principle;
- Functional control principle;
- General specification principle;
- Responsibility principle.

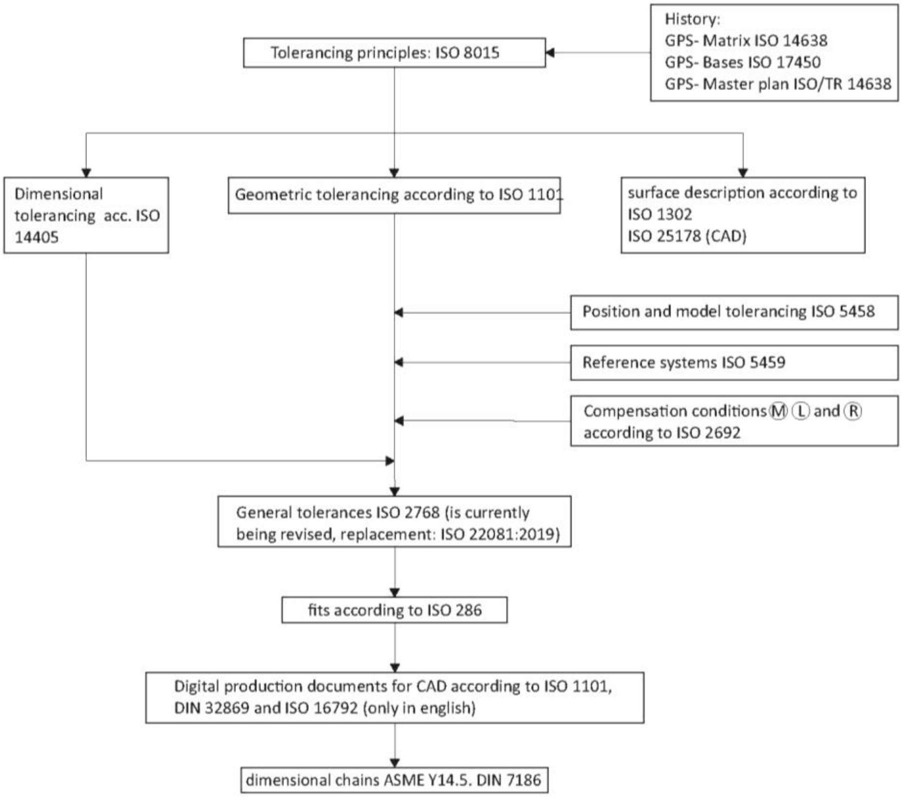

Figure 2: ISO/GPS tolerancing system [1].

A small overview of some key standards to understand the GPS system is listed in references [3].

2.3 Focus of the GPS system

GPS has been designed especially for the machine building industry. It solves contradictions and inaccuracies of tolerance specifications and verifications by a consistent set of standards building a system. Most of the tolerance definitions specify operations of 3D-coordinate measuring equipment. The

definitions of the symbols in a draft are created in a way that database features of 3D-CAD-systems could be used instead of simple text. The system is quite complex and the drafts are potentially very difficult to read (Figure 3).
The possibilities of defining tolerances for non-rigid parts are given, but poor compared to the needs of the wood and furniture branch. Parts with soft or porous surfaces are not taken into account. Moisture of workpieces are also disregarded, only the standard climate for measuring humidity can be specified.

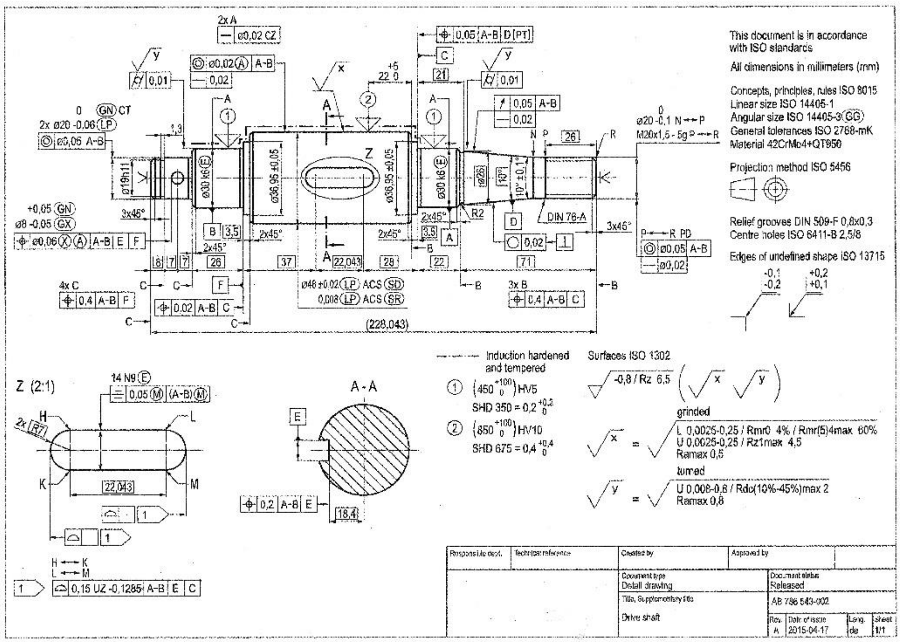

Figure 3: Example of a shaft according to the GPS system [1].

3 GPS IN THE WOOD AND FURNITURE INDUSTRY

At the moment, the GPS system is more or less unknown in the wood and furniture branch. Besides the question, if there is a need to use it or not, the system might be applied unconsciously. One rule of the system explained in ISO EN DIN 8015 is the principle of invocation. If a standard of the system is used in a draft, e.g. a symbol for position tolerances, the whole system is valid automatically. It can be switched off by a mandated indication via the draft heading block.

But there is a need to use the GPS system in the branch and to adapt some rules for the special needs. In consequence, new activities in standard committees will be needed. In the VDI working group FA102, a workshop was held on Nov. 29th, 2017 in Lemgo and some activities have already been initiated.

3.1 Design features and tolerances

It is not necessary to discuss the complete GPS system, because some tolerances are simply not applied in the branch. All form tolerances for round turned workpieces, such as run and cylindricity are only needed in the niche of turnery.

Carcass furniture is a major product of the branch. The following explanations will be executed by the example of a typical European kitchen cupboard. The sides have lines of drill holes, so position tolerances are needed to ensure parallel and horizontal shelves. The chain of dimensions and tolerances for guaranteeing the functionality is quite long and complex, but also rather rough. The backboard of the cupboard is important for the rectangularity as seen from the front side. If the backboard is nailed or screwed, the rectangularity is given by the corpus press. If not, the width and length with their tolerances, combined with the depth and parallelism of the backboard grooves in the side walls and the fixtures, build a dimension chain. Depending on the straightness of the backboard side, the back is only supported by the heights in the groove. Standard depth measuring of the groove is a non-capable method (Figure 4), a touching patch is needed [4]. The sides, the back, the top, and base are fixed by glued dowels or additional fixtures. The dowels and therefore also the boreholes in the sides as well as in the top and the base assure the position accuracy. There are only a few scientific investigations on which tolerances are actually needed [5]. One result of the previously mentioned VDI workshop was that most of the tolerances specified nowadays might be too small, simply because the designer does not know what is needed to assure functionality and appearance. He intends to be on the safe side.

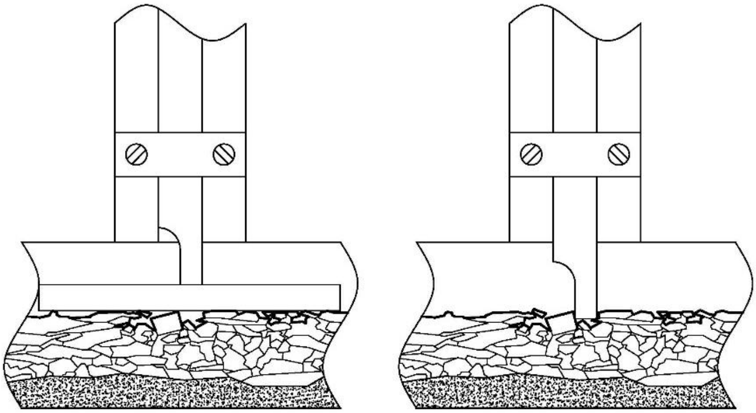

Figure 4: Measuring the depth of o groove in a side of a cupboard.

3.2 Possible improvements by the GPS system

The GPS system is a complete and consistent system to specify and verify the geometrical characteristics of workpieces. Therefore, also the wood and furniture industry can benefit from the system in general and avoid misunderstandings and unprecise workpiece descriptions. The major problem is the huge gap between what is practice in the branch at the moment and the state of the art given by the system. There is almost no education for dimensioning and tolerancing in specific institutions educating specialists for the branch. The pressure caused by the introduction of the GPS system will lead to a more sophisticated education and awareness in the future. But when looking through the chains of the GPS system, improvements for the branch can be identified today.

Chain link A

The enhanced GPS coding forces the designer to be more aware of the characteristics actually needed. At the moment, there are no examples of how to use the GPS coding in the branch. If this is given, the extra time invested to complete a standard draft conformal to GPS will be small. Special codes for the specific features e.g. related to appearance will be needed.

Chain link B

At the moment, only a few companies use tolerances in their drafts constantly. DIN 68100 is a fitting tolerance system for dimensions of wood-based products, but not compatible with GPS. Position and form are only scarcely specified. The standard for assigning specific requirements to surface quality characteristics is based on retained samples. In most cases, the requirements for these are not listed. The workpieces simply have to be similar to the samples. The definitions of the GPS system for non-rigid parts are difficult to handle regarding standard parts of furniture.

Chain link C

With the exception of dimensions, quantitative definitions are avoided, especially for the important feature of appearance or surface quality. A standard for quantifying is needed to guarantee a wider application according to GPS. VDI 3414 is a step towards this goal. The major problem of assigning dimensions of wood-based panels' properties is the porous surface. Here, the GPS offers special filters for identifying e.g. tangentially touching counterparts. The best-in-class companies are introducing coordinate measuring equipment now, but there is no practical idea on how to use it precisely. GPS can help but has to be adapted to the specific cases.

Chain link D

If all specifications are given by a complete and consistent draft, there will be no discussion about conformance or non-conformance. Maybe this will remain a dream in relation to surface characteristics for appearance.

Chain link E

The GPS system will ensure a better way of measuring. Besides the problems already discussed above, the moisture content and the combined shrinkage and swelling are the biggest issues here. DIN 68100 gives a direction on how to measure and how to estimate the dimensions if the moisture content is not according to the specification. Statistical tolerancing offers a more sophisticated way of estimating the probable dimension [6] or form [7]. The problem is then not limited to chain link E and the GPS works very simple here by just demanding a specific room climate for the measurements. This might be enough for standard measurements in the automotive or machinery industry. In the wood and furniture industry, it takes too much time until the equilibrium moisture content for a specific room climate is reached. Further investigations are needed here to allow an estimation of a dimension out of measurements within the GPS system.

Chain link F and G

The equipment in use does not vary much between the branches and there might be no specific reason to apply these chain links to the wood and furniture industry. But with shrinkage and swelling, the measurement of moisture content comes in. In relation to the claimed tolerances in the branch, it does not make any sense to think about measurement capabilities at the moment. Most of the applied techniques are far away from measuring moisture content with an accuracy good enough to guarantee the claimed tolerances. All standards used do not have any relation to the GPS system at the moment. Also here, the GPS forces a consistent and systematical procedure.

3.3 Example

The following example of an incomplete draft (Figure 5) gives an overview of the application of GPS in the carcass furniture industry. The applied tolerances are not realistic and merely samples.

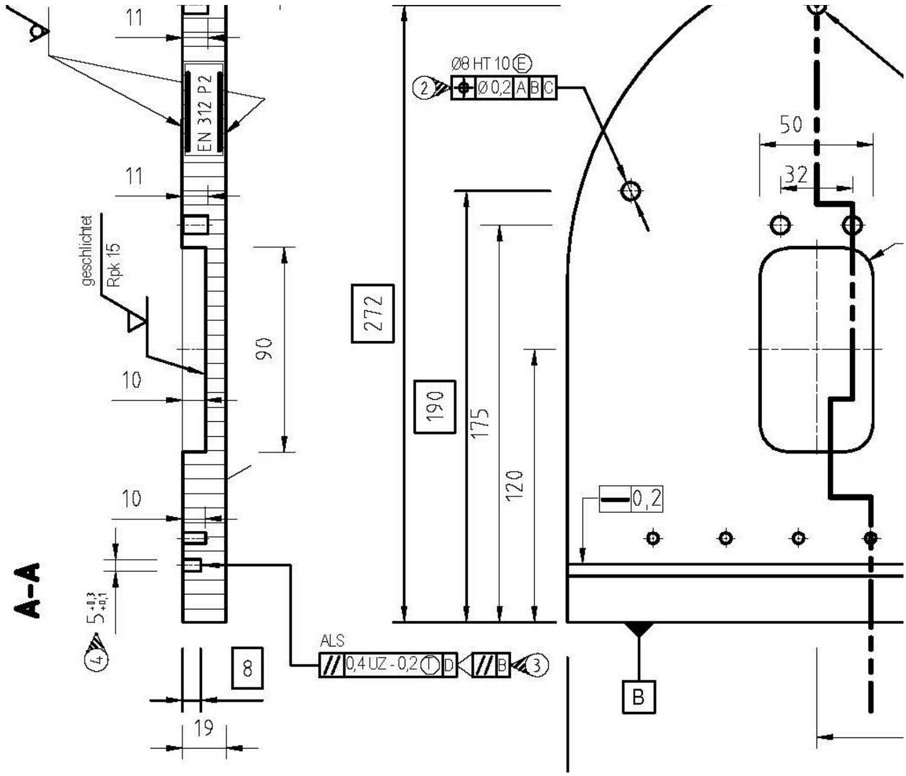

Figure 5: Part of a draft of a wood-based panel with few tolerances.

4 CONSEQUENCES AND FUTURE PROSPECTS

The actions mentioned above have already been received by the working group FA 102 of the VDI. This group belongs to the German national society of engineers and is only able to submit guidelines, not standards. At the end of this year, a workshop will be held together with the central federation of the wood industries in Germany. The committee of the DIN is informed and planning actions, but GPS is an international standard. A master plan is needed to coordinate worldwide activities to introduce GPS in the wood and furniture branch. The benefits caused by the introduction are worth it. The following steps should be included in the master plan:

- Scientific researches on the tolerances needed to guarantee the function of typical products.
- Further research in statistical tolerancing combined with moisture changes.
- Coding standards for features of appearance.
- Investigations on measurement procedures for porous and non-rigid wood-based materials with the aim to define distinct algorithms.
- Investigations of the capability of typical measurement operations.
- Standards for sensory testing procedures, that these standards could be included in the GPS system.
- Inclusion of process verification techniques to enlarge the benefits of the GPS system.

The aim should be to define complete chain links for important features, e.g. in the carcass furniture industry.

STANDARDS GPS SYSTEM AND OTHERS

ISO 1101:2012: Geometric Product Specifications (GPS) – Geometrical tolerancing – Tolerances of form, orientation, location, and run-out

ISO 16792:2015: Technical product documentation – Digital product definition practices

ISO 8015:2011: Geometrical product specifications (GPS) – Fundamentals – Concepts, principles and rules

ISO 2768-1:1989: General tolerances – Tolerances for linear and angular dimensions without individual tolerance indications

ISO 2768-2:1989: General tolerances – Geometrical tolerances for features without individual indications

ISO 5459:2011: Geometrical product specifications (GPS) – Geometrical tolerancing and datum systems

ISO 5458:1998: Geometrical Product Specification (GPS) – Geometrical tolerancing – Positional tolerancing

ISO 2692:2006: Geometrical Product Specification (GPS) – Geometrical tolerancing – Maximum material requirement (MMR), least material requirement (LMR), and reciprocity requirement (RPR)

ISO 286:2010: Geometrical product specifications (GPS) – ISO code system for tolerances on linear sizes

ISO 10579:2010: Geometrical product specifications (GPS) – Dimensioning and tolerancing – Non-rigid parts

VDI 3414-1:2014

VDI 3414-2:2014

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LIQUID WATER PERMEABILITY OF WOOD FINISHED SURFACES

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Abstract
The aim of this study is to investigate the influences of coatings used for wood furniture finished surfaces on the liquid water permeability. The assessment of liquid water permeability is based on the European standard EN 927-5 coating materials and coating systems for exterior wood. In the contribution there is investigated influence used coating materials, repeating times of wooden samples with finished surfaces floating surfaces on the amount of absorption of water in the coating films of finished surfaces and coating wooden samples. The results can improve the knowledge of the durability of coating materials for finishing product made from wood and determinate to exterior wood.

Keywords:
Water permeability, Finished surfaces, Spruce, Acacia, Polyurethane lacquers, Synthetic opaque lacquer

1 INTRODUCTION

The design of exterior coatings for massive wood requires control of many factors in order to maximize the durability of wood products. Water plays the key role in several degradation mechanisms. Water in wood becomes among the factors with the influence on the durability of wood products in the exterior. Water absorption by wooden samples with finished surfaces can modify the physical properties of coatings and wood. Water can cause transmission through the coating swelling, shrinkage, and movement of the wooden substrate. When it is spoken about the liquid water in wood it is used the terms water absorption and water permeability Water absorption is the ability of a coated or uncoated wood panel to absorb water from liquid or vapor. When coating system to allow the transmission of water as liquid or vapor, we speak the ability called water permeability. The high permeability of some kinds of wood is at variance with many of the requirements of moisture control. In our contribution, the research is aimed at considering the role of water in exterior wood coating behaviors.

The main tasks of the investigation are:

- How does the amount of water permeability and water absorption influence the properties of coating systems?
- How does the kind of wood on water permeability and water absorption influence finished surfaces?
- What influence does the kind of applied coating material on water permeability and water absorption have on tested samples?
- What type of influence does the number of repeated cycles of floating on water have for the quality of finished surfaces?

It is important to recognize that the transport of liquid water in organic polymers, that means in wood, as organic polymers, is mainly controlled by diffusion [2] [3] [4]. The diffusion through the matrix due to the concentration gradient can be of two different mechanisms, activated diffusion through the homogenous polymer matrix and non-activated diffusion through pores and defects. Contents of pigments adding to the coating materials have very important influence in permeability of water going through the coating films. The diffusion in the homogenous polymer matrix can be divided into three basic cases [1]:

- Case I or Fickian diffusion, where the speed of diffusion is much smaller than the speed of relaxation in the polymer.
- Case II diffusion, where the speed of diffusion is very fast in comparison with relaxation processes.
- Non-Fickian diffusion, which appears when the speed of diffusion and relaxation are comparable. [5]

When measuring the permeability of water and moisture through coatings on wood is normally higher than the measured permeability through free films. They report the following reasons for this discrepancy:

- The uneven swelling of the wood substrate compared to the swelling of the coating.
- Fibers from the substrate penetrate the coating film, thus reducing the net thickness.
- The interface between the coating and the wood is larger than its geometrical surface.
- The surface of the wood is more hydrophilic than the coating.
- Cracks and inhomogeneity of the coating on wood are difficult to control. [6]

The aim of this article is to investigate the influence of the multiple reps of water floating on the quality of finishing and on water absorption by finished surfaces from point of applied coating materials, finished kinds of wood the number water floating of repetitions. The specimen was tested according to European standard 927-5: 2006 paints and varnishes, coating materials and coating systems for exterior wood – part 5 assessment of the liquid water permeability.

2 USED METHODS

2.1 Principle

The coating under test is applied to the face of defined test panel where the remaining face and sides are carefully sealed using a sealer of defined mandatory low permeability. The samples are floating face down by the tested finished surface for 24 h in one cycle. The properties of water permeability are assessed by measuring the mass of water uptake over a 72 h period of a coated test panel exposed to liquid water.
Results are expressed as water absorption of coated wood panels in grams per square meter test surface per 72 h.

The used equipment was an air conditioner, laboratory weight Kern, and a laboratory temperature oven.

2.2 Testing procedure of prepared samples

- 24 h floating face down in deionized water, such that the test face is fully submerged in accordance with standard ISO 554.
- 3 h drying at (20 ± 2) °C and a relative humidity of (65 ± 5) % in accordance with ISO 554.
- 3 h drying at 50 °C.
- 18 h drying at (20 ± 2) °C and, relative humidity of (65 ± 5) %.
- After the absorption cycle, the test panels are weight to the nearest 0.01 g and compared to the initial mass before *(m_o).*
- After 72 h remove the test panels from the water, blot lightly to remove any water droplets and wig. Record elapsed time and mass m_1,
- $m_1 – m_0 = m$
- Water absorption per square meter of the test surface for the test panels by dividing the water uptake by the measured test area of each of the test panels.

Tested samples of wood
Massive spruce (Picea abies) dimensions (150 ± 2) mm x (70 ± 2) mm x (20 ± 2) mm 5 samples; massive acacia dimensions (150 ± 2) mm x (70 ± 2) mm x (20 ± 2) mm, 5 samples, glass dimensions (150 ± 2) mm x (70 ± 2) mm x (20 ± 2) mm

Tested coated materials
AXAPUR gloss U1010 transparent polyurethane lacquers, solvent opaque lacquer Profi Lazúra S1025

3 RESULTS

In Table 1 and in Figure 1, the results of the investigation are presented on the influence of number repeating the floating tests on the water permeability and water absorption of the tested samples. That means the ability of a coating system to allow the transmission of water as liquid or vapor. In Table 1, there is the ability of water permeability expressed as the stable mass we can achieve.

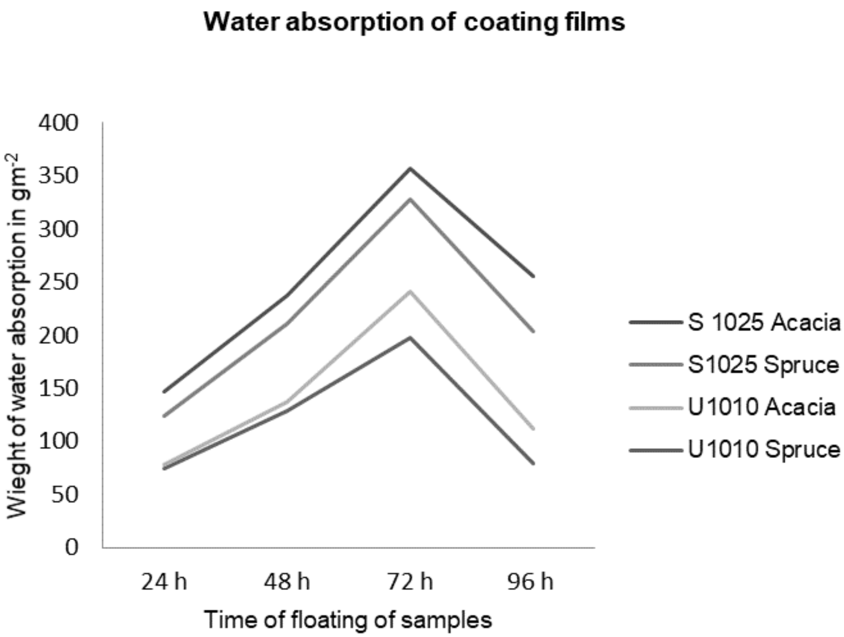

Figure 1: Dependence of water absorption on the floating time on the applied coating materials Axapur U1010 and S 1025 on the used kinds of massive wood spruce and acacia.

Table 1: Water permeability depending on the used coating materials and massive wood materials.

	Units	tested finished surfaces			
Coating		U1010	U1010	S1025	S1025
Massive surfaces		Massive spruce	Massive acacia	Massive spruce	Massive acacia
Sorption 1 cycle 24 h floating 72 h drying					
Mean value	$g.m^{-2}$	74.27	3.60	46.00	22.80
Maximum	$g.m^{-2}$	111.33	5.33	53.33	26.00
Minimum	$g.m^{-2}$	53.33	2.00	28.67	16.67
Standard deviation	$g.m^{-2}$	21.19	1.16	9.05	3.36
confidence level **α**	%	95	95	95	95
Sorption 2 cycle 24 h floating (together 48 h of floating 144 hours of drying					
Mean value	$g.m^{-2}$	128.67	8.80	73.73	26.27
Maximum	$g.m^{-2}$	146.00	9.33	88.00	28.67
Minimum	$g.m^{-2}$	112.00	8.00	56.67	23.33
Standard deviation	$g.m^{-2}$	11.10	0.50	12.21	2.17
confidence level **α**	%	95	95	95	95
Sorption 3 cycle 24 h floating (together 72 h of floating 216 hours of drying					
Mean value	$g.m^{-2}$	197.47	43.60	86.13	29.60
Maximum	$g.m^{-2}$	262.67	52.67	96.00	31.33
Minimum	$g.m^{-2}$	139.33	32.00	69.33	28.67
Standard deviation	$g.m^{-2}$	45.16	7.26	9.86	1.00
confidence level **α**	%	95	95	95	95
Sorption 4 cycle 24 h floating (together 96 h of floating 288 hours of drying					
Mean value	$g.m^{-2}$	79.33	32.80	90.80	51.87
Maximum	$g.m^{-2}$	91.33	45.33	103.33	57.33
Minimum	$g.m^{-2}$	68.00	20.67	82.67	45.33
Standard deviation	$g.m^{-2}$	9.34	8.71	7.17	4.39
confidence level α	%	95	95	95	95

In the Tables 2, 3, 4, and 5 there are presented the outcomes of the statistical evaluation of the reached results introduced in this contribution.

Table 2: ANOVA statistical test of Axapur Lesk U1010 on spruce.

ANOVA						
Source of variability	**SS**	**Difference**	**MS**	**F**	**Value P**	**F krit**
Between selections	11.049	3	3.68306	19.406	1.4E-05	3.2389
Entire selections	3.0366	16	0.18978			
total	14.085	19				

Table 3: ANOVA statistical test of Axapur gloss U1010 on acacia.

ANOVA						
Source of variability	**SS**	**Difference**	**MS**	**F**	**Value P**	**F krit**
Between selections	1.2328	3	0.41094	44.912	5.1E-08	3.23887
Entire selections	0.1464	16	0.00915			
total	1.3792	19				

Table 4: ANOVA statistical test of Profi Lazura S1025 on spruce.

ANOVA						
Source of variability	**SS**	**differ**	**MS**	**F**	**Value P**	**F krit**
Between selections	1.3651	3	0.455032	17.039	3.09E-05	3.23887
Entire selections	0.42728	16	0.026705			
total	1.79238	19				

Table 5: The ANOVA statistical test of Profi Lazura S1025 on acacia.

ANOVA						
Source of variability	**SS**	**differ**	**MS**	**F**	**Value P**	**F krit**
Between selections	0.580895	3	0.19363	75.934	1.11E-09	3.23887
Entire selections	0.0408	16	0.00255			
total	0.621695	19				

Mass of water absorption during one cycle was recorded in Figure 2 and 3. In these figures, it is possible to observe the influence of repeated cycles in depends on the applied finished materials and finished massive kinds of wood.

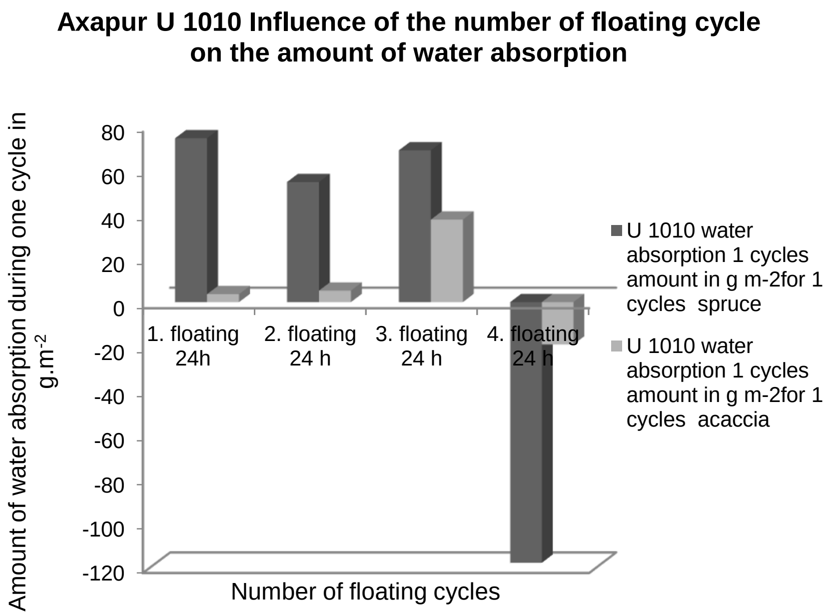

Figure 2: U1010 influence of the number of floating cycle on the amount of water.

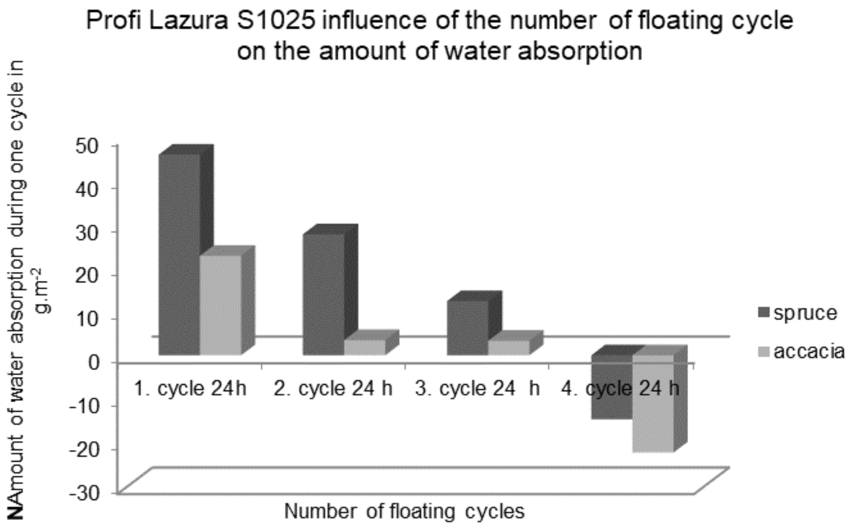

Figure 3: S1025 influence of the number of floating cycle on the amount of water.

In the next step, there was investigated the influence of 96 hours floating on tested finished surfaces on the change of gloss. The change of gloss is a degree of coating materials degradation. The gloss tested surface was measured under the angle of 60 degrees according to the standard ČSN EN ISO 2813 (673066). Results of the assessment change of the gloss surface are shown on Figure 4.

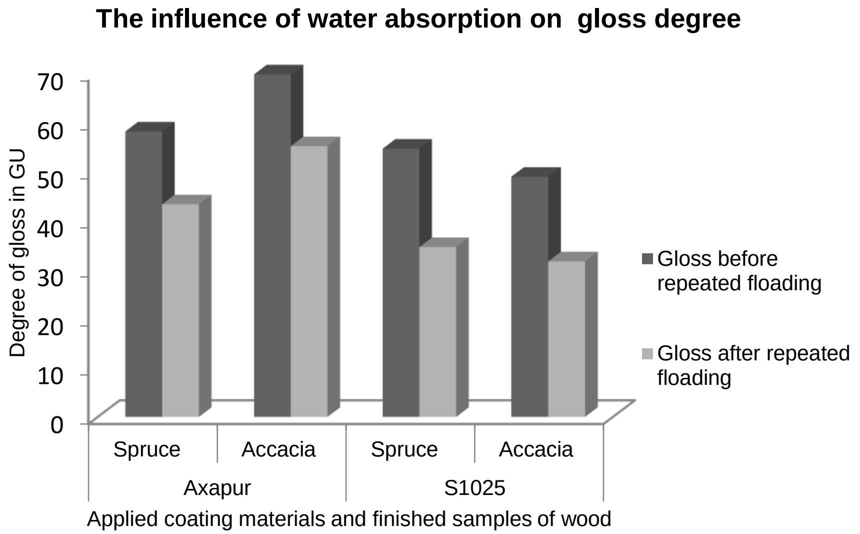

Figure 4: Gloss of finished surfaces by Axapur U1010 and S1025 before floating and after 96 hours of floating.

4 CONCLUSION

The identification of water absorption and water permeability is part of the standard set of tools at the disposal of the evaluation resistance of organic coating against the influence of water. Summarizing the entire results, these are the conclusions:

- The influence of the kind of wood on the amount plays a very important role in the water permeability and water absorption. Within the used massive material the acacia performs better for outdoor application of wood than spruce.
- Dominant effects on coating water permeability and water absorption play chemical contents and polymer bases of coating materials. Samples finished by polyurethane coating materials marked less amount of water absorption than synthetic coating materials. Polyurethane coating materials are curing and have the thicker polymer net and so they are more resistant to water absorption. The chemical base of coating materials is a very important factor on which the water permeability depends. On Figure 1 and in Table 1 the differences between synthetic paint S 1025 and U 1010 are shown, where U 1010 is more applicable for finishing massive kinds of wood for exterior exposition than the type S 1025 made from synthetic materials.
- The time of exposition finished surfaces to water during the floating has an impact on the aging of coating films without the influence of kinds of

wood and chemical bases of coating materials. Gloss changes can be observed as the degree of coating film degradation. Especially more significant changes exhibit the samples finished with synthetic coating films.

ACKNOWLEDGMENT

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FURNITURE DESIGN AND 3D PRINT

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Abstract
The objective of the paper is to demonstrate new trends in design furniture and 3D print. In 3D technology, 3D printing is at the forefront of technological innovation. This is also the case with furniture. Several technologies and starting materials (plastic, metal, ceramics, etc.) can be used to produce the mechanical properties of the formed part. For some technologies, even color printing is possible. 3D printing also belongs to unconventional machining methods, even if it is not a classical machining where the material is removed from the blank. 3D joints are therefore suitably payable where fast disassembly, product weight reduction, object variability or color variation are required. The products then work on the principle of a construction kit, which can be simply and quickly folded or decomposed or transformed into another variant. How to verify the mechanical properties of 3D printing is important for furniture design. Practical examples of using 3D printing in design work.

Keywords:
Design construction, Furniture design, 3D print, Prototype

1 INTRODUCTION

The 3D print is unconventional machining method. It is not a classic machining process, where the material is removed from the blank, but instead, it is added to the emerging part. It is the technology of additive production. The final product is made by the gradual application of the material after very thin layers, which can be joined together, for example by gluing or melting. Unlike conventional production methods, 3D printers can create complicated shapes and designs that cannot be made by any other methods. The 3D printing is especially suited for the quick preparation of production for pieces and small-lot production. Most it is used for prototype production.
Different types of 3D printers use different printing technologies that process different materials in different ways. It is important to know that the type of the 3D print and used material are the most basic limitations of 3D print – it does not exist a universal solution suitable for all types of applications. For example, some types of 3D printers are processing powder materials (nylon, plastic, ceramics, metal), are using light or heat source to cure (melt) merging individual layers of powder to form a defined shape. Other 3D printers use a

liquid photopolymer, which is then cured by light or laser beam into extremely thin layers.

Figure 1: Mountain bike MX-6 Evo with a titanium frame, which was made on SLM 3D printer. [1]

The similar technology is blasting fine droplets of photopolymer materials. This technology remotely resembling classic inkjet printing. Probably the most common and the most famous 3D printing technology is thermoplastic extrusion modeling (FDM or FFF technology) used by most 3D printers designed for the public segment. Because parts can be printed directly, it is possible to produce very detailed and complex objects without the need for final assembly.

2 RAPID PROTOTYPING

With 3D printing, Rapid Prototyping (RP) is often closely associated. RP is a progressive set of technologies that is based on the principle of creating a computer model, spreading the model into thin layers and then processing it into a real product using a 3D printer. Data is created using 3D CAD programming systems. This technology is used in many industries - consumer, engineering, medicine, aviation, and is being used in the furniture industry.

Figure 2: Alien chair, ABS-PC, author: Ing. Martina Šebková. [2]

Table 1: Basic technologies of 3D print – Rapid Prototyping (RP).

Basic technologies of RP	Shortcut	Material of model
Stereolithography	SLA, SL	Photopolymer
Solid Ground Cutting	SGC	Photopolymer, nylon
Selective Laser Sintering	SLS	Polyamide, nylon, wax, metal powders
Laminated Object Manufacturing	LOM	Paper with one-sided binder
Fused Deposition Modelling	FDM	ABS, wax, polycarbonate
Multi Jet Modelling	MJM	Thermopolymer, acrylic photopolymer

The producing process is often divided into three main parts – pre-processing, processing and post-processing. The first part includes all steps related to data preparing. For example, transfer of data from CAD software to STL file, where is geometric shape divided to file of polygons. The final object is formed by tiny layers (0,2–0,05 mm) step by step as already mentioned and therefore it is necessary to secure the so-called supporting structure of the layers in a more complicated building to avoid collapse or deformation during printing itself. Supporting construction is not necessary for all 3D printing methods.

Figure 3: Example of printed 3D joints. [3]

3 3D PRINT IN FURNITURE DESIGN

In the following research are mainly included shelving systems of different types using 3D printing technology. The first example is the shelving system Shelf, which applies 3D printing technology to connect single boxes to a shelving wall (Figure 4). The fasteners form colored crosses that are inserted into the pre-drilled hole so as to prevent their displacement. For small assemblies, the manufacturer recommends joining with 3D printed elements. For larger assemblies, the manufacturer recommends metallic elements to ensure greater shelf system integrity.

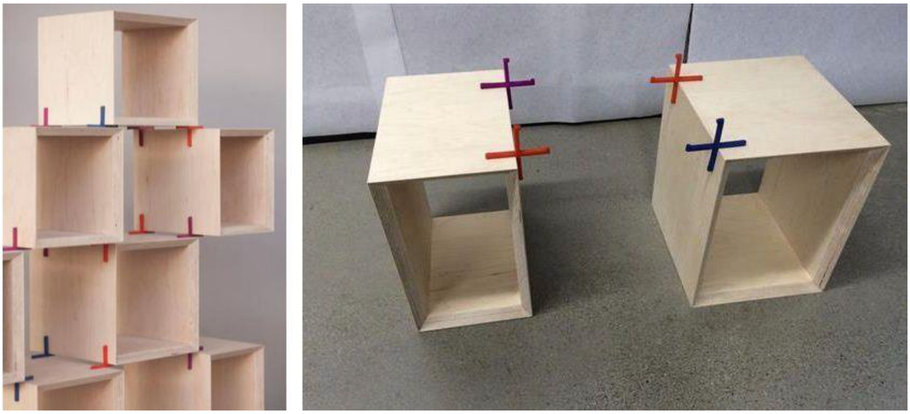

Figure 4: Example of printed 3D joints. [4]

Suple (Figure 5) presents furniture fixation system where the legs are connected by one joining element. This joining element was printed by the 3D printer. The printed joint is then used to form a silicone mold so as to capture the negative shape of the joint. The wax used to make molds from gypsum or ceramics was applied to the negative form. The hot wax evaporates from the mold and its place will take a metal. This results in a metal joint.

Figure 5: "Suple" - Great things to people (gt2P). [5]

Designer Kenny Hong exhibited his first 3D printed furniture at the 2015 International Furniture Fair in Singapore when he was twenty years old. There were two original exhibits partly made by 3D printing technology (Figure 6).

Figure 6: ‘The Burning Bush Telephone Pod’ and ‘The Sheep Mirror’ Designer Kenny Hong. [6]

Experimental construction by Jiří Dias consists of vertical and horizontal parts of solid wood of two different diameters. The supporting elements are connected by joint, which is made by 3D printing technology (ABS material). The principle of the joint consists in the simple clamping of the connecting element on one supporting part, into which is then fastened another rod of smaller diameter, which is also a rack of the shelf (Figure 7).

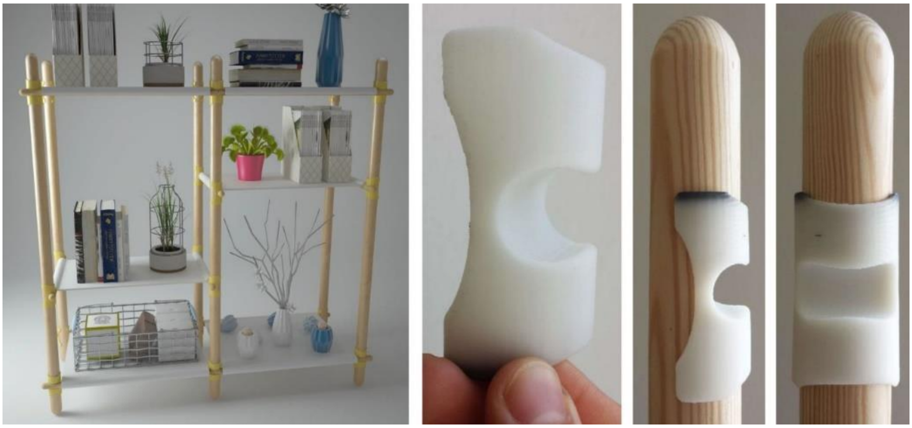

Figure 7: Shelving system and detail of the joint, author: Jiří Dias [7].

Another possibility to use the new 3D printing technology is a shelving system designed by Ollé Gellért. This system is made up of joints that can be bought on the Internet for a fee and then printed using your own 3D printer. The joints are designed to connect 8 mm thick plywood to a variety of furniture products (Figure 8).

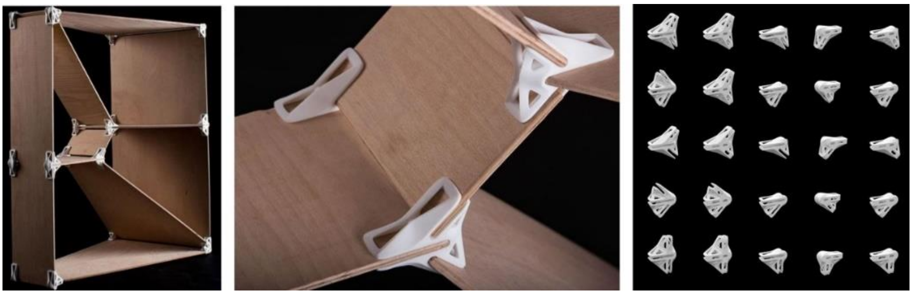

Figure 8: Shelving system with 3D printed joints – Ollé Gellért [8].

4 VERIFICATION OF MECHANICAL PROPERTIES

How to proceed to verify the mechanical properties of a 3D printed element are presented in the final thesis of Iva Linhartová at Mendel University in Brno.

The above-mentioned shelving system designed by Ollie Gellért was chosen for verification (Figure 8).

4.1 Influence of layer thickness on stiffness

To analyze the influence of layer thickness on the stiffness of the component were tested two 3D printed components with different layer thickness. The first component was printed using a layer thickness of 0.20 mm, second 0.25 mm. According to different studies dedicated to the influence of layer thickness on 3D printed material's mechanical properties [10, 11]; the thinner the layer is, the better the overall stiffness of the material.

4.2 Visual analysis of the component's surface response

Making a visual evaluation of the surface of the component, the difference in the layer thickness can be spotted. The surface of the component printed with thicker layer seems more rough and inaccurate. The component with a layer thickness of 0.25 mm had more visible cracks along the fibers (Figure 9). Fibers in the more stressed areas of the component's geometry were buckled or de-laminated (Figure 9). Part of the jaw cracked along the fibers and fall off. The compressive stress influence was mostly visible on the downer jaw of the component, which buckled to the sides as the component was loaded gradually. The component with a layer thickness of 0.20 mm had a bigger buckling of the jaw because it holds under bigger compressive force. [8]

Figure 9: (from left) Component with layer and component with a layer thickness of 0.20 mm thickness of 0.25 mm [9].

4.3 Failure analysis

On the working diagrams (Figure 10, 11) obtained by analyzing data from the testXpert II software, we can see the approximate characteristics of two components with different layer thickness and their stress behavior. The peak stress of the component with a layer thickness of 0.20 mm was approximately 22 % higher than the peak stress of the component with 0.25 mm layer thickness. The maximum force for component with 0.20 mm layer thickness was 424 N, and the maximum force for the component with 0.25 mm layer thickness was 334 N. [9]

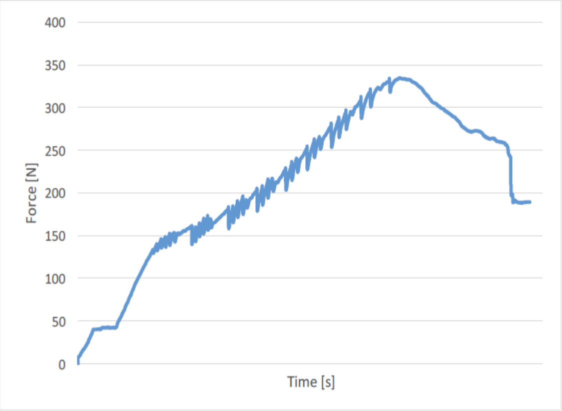

Figure 10: Working diagram of the pressure test, component with a layer thickness of 0.20 mm [9].

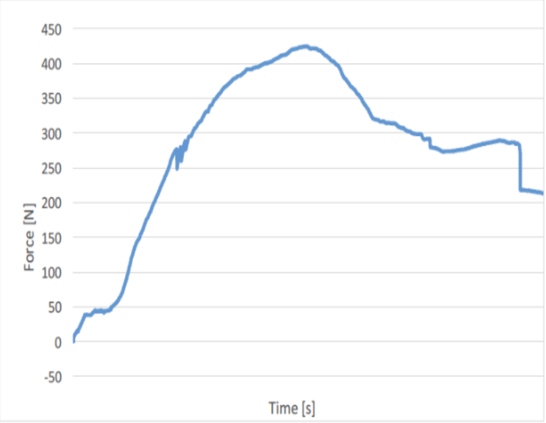

Figure 11: Working diagram of the pressure test, and component with a layer thickness of 0.25 mm [9].

To analyze an influence of layer orientation when 3D printing a component, numerical models with parametrical options were created. Only the material model was defined parametrically. The geometry was made based on import (see above). Two numerical (FE) models were compared between each other. The displacement in Z-axis direction is shown in Fig. 12. We see, that the most deflected (displaced) parts of the component is top and bottom, meanwhile the center (red color) is rather static. All results below are showed in RSYS = 11 that considers the rotation of forces. So the results are not depicted with respect to the geometrical axis of the specimen.

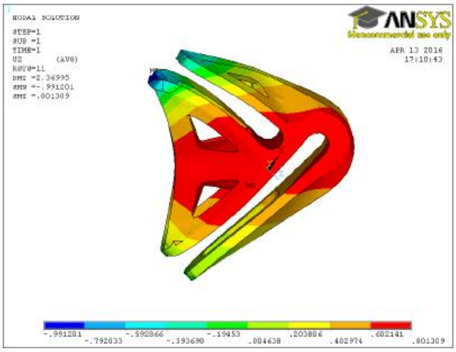

Figure 12: Displacement in Z-axis direction in [mm] [9].

Displacement in X-axis direction is depicted in Fig. 13 (horizontally in the Figure). There is a symmetric distribution given by boundary conditions.

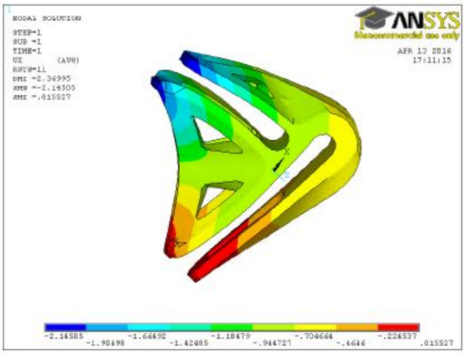

Figure 13: Displacement in X-axis direction in [mm] [9].

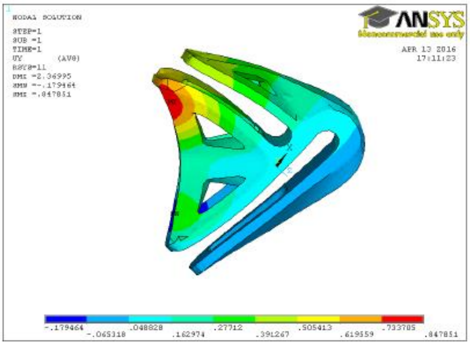

Figure 14: Displacement in Y-axis direction in [mm] [9].

Because we have a nearly isotropic material mode, we may use also energetic criteria for assessing stress peaks. For this purpose, we plotted von Misses stress that shows where the scalar stress is the highest. In other words, it shows the areas of the highest potential for failure of the material. As we see in Fig. 15, the highest stress is on the top of the sample. This stress is called singular stress and is invalid stress that occurs due to a fact the area forces are acting at, are approaching zero. If we exclude these parts of the component from the mode, we may see where the component is likely to fail. It is the vertical rib that experiences a stress of about 70 MPa. As we showed in Fig. 9, the failure really first occurred at vertical ribs by delamination. Our model is homogeneous, so it cannot explain and characterize the delamination phenomenon. [9]

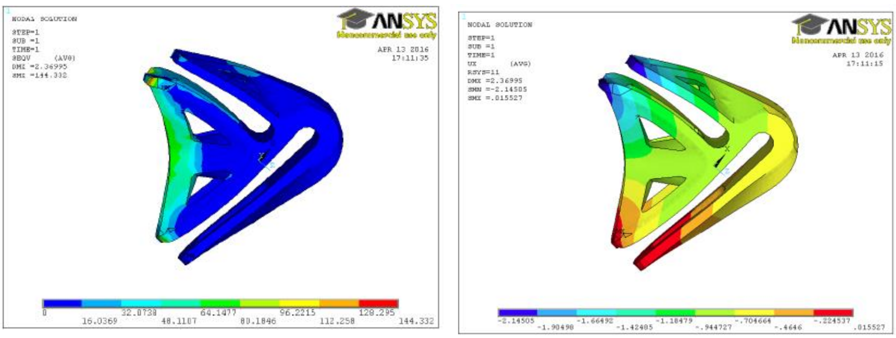

Figure 15: (from left) Import to ANSYS 15.0 and displacement in X-axis direction in [mm] [9].

5 DESIGNING NEW FURNITURE PRODUCTS WITH 3D TECHNOLOGIES

In the Atelier of Furniture Models, several furniture products were designed by students, which used 3D printed joints in construction. 25 functional models were made. These are completely original designs that will need to be tested for strength testing. In this paper, we are presenting first designs of using 3D print from design furniture field. The various product collection was designed - hanging clothes - a hanger as a solitaire in the room, coffee tables, a dumb servant and even lighting.

Figure 16: Visualisations of furniture products.

Figure 17: Photos of functional models where the 3D print technologies were used.

Figure 18: Photo of functional coffee table model where the 3D print technology was used.

6 SUMMARY

3D printing is becoming the forefront of technological innovations within the detachable joints. Several technologies and source materials can be used in production so the mechanical properties will depend on the chosen materials. For some technologies, even color printing is possible. The 3D printer can also produce what is impossible for conventional machine tools. We talk mainly about the shape. For conventional machining, the shape is limited by the shape of the tool, while 3D printing allows creating any complex shape without unnecessary waste.

Therefore 3D joints are useful where fast disassembly, product weight reduction, object variability, or color variation are required. The products then work on a modular basis, which can quickly and easily be folded or spread or transformed into other variants.

To analyze the influence of layer thickness on the stiffness of the component, two 3D printed components were tested in compression with different layer thickness and the results confirmed that the thinner the layer is, the better overall stiffness of the material.

The numerical model revealed the highest potential for failure of the material and where the component was likely to fail. At the compression test of the 3D-printed component failure first occurred at vertical ribs of the component by delamination, as it was expected according to the numerical model.

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SESSION F
Supply Chain Design and Management 2

SUPPLY CHAIN DESIGN: LOCATING DISTRIBUTION WAREHOUSES WITHIN A GROUPAGE NETWORK SETTING

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Abstract
Just in time-deliveries require reliable transports. If warehouses are operated by service providers, the location decision may arise periodically. Traditional warehouse location models are not designed to realistically consider transports in groupage networks. Also, traditional transport pricing is not based on a costs-by-cause principle but rather evolved due to previous state regulation. This paper tries to evaluate the impact of warehouse location decisions on transportation times and operations cost in a groupage network setting while taking into account other influences on service provider pricing.

Keywords:
Warehouse location, Logistics service provider, Cost allocation, Pricing model

1 TRANSPORTATION NEEDS AND LOGISTICS SERVICE PROVIDERS

In a volatile and uncertain market environment, storing goods for a long period is capital-intensive and connected with value risks (e.g. deterioration, price-drop or loss of customers). Therefore, many manufacturers and retailers want to receive their goods ‘just in time’ to avoid the related risks. This has led to an increase of shipments requiring highly reliable and synchronized groupage networks, bundling shipments from and to multiple locations.

In order to lower cost and to be more flexible, many companies outsource logistics activities to logistics service providers (LSP). In this paper, an LSP is a company whose core business consists of executing physical and/or administrative COST-activities (<u>C</u>ross Docking, <u>O</u>rder Picking, <u>S</u>toring and <u>T</u>ransport) on behalf of other companies [1, 2].

Consider the case of an industrial company with one given factory producing make-to-stock-goods (e.g. standard packaging material) and nationally distributing them to many customers in a ‘few-to-many’-setting with wide-spread small shipments.

Outsourcing is especially common for small size and for irregular shipments [1, 3]. This enables companies to switch LSPs frequently, sometimes on a single transaction basis (e.g. via freight exchange platforms). Building and operating warehouses used to be a long-term investment. Nowadays, many companies outsource their warehouse operations in a bundle with transport and value-added services (e.g. special packaging, assembly, repair or IT-related services).

These so-called ‘contract logistics projects’ are frequently subject to three to five-year contracts [4]. Therefore, in this scenario, the question for the supplier arises every few years, not only which LSP to choose, but also where to locate the distribution warehouse.

This paper assumes that the following tasks have been outsourced, possibly even to several different LSPs (Figure 1):

(a) Regular shuttle transport from the factory (‘source’) to the warehouse (‘sink’).
(b) Storing and order picking in the warehouse.
(c) Regular distribution transport from the warehouse (‘source’) to the wide-spread customers via a groupage network (‘sinks’).

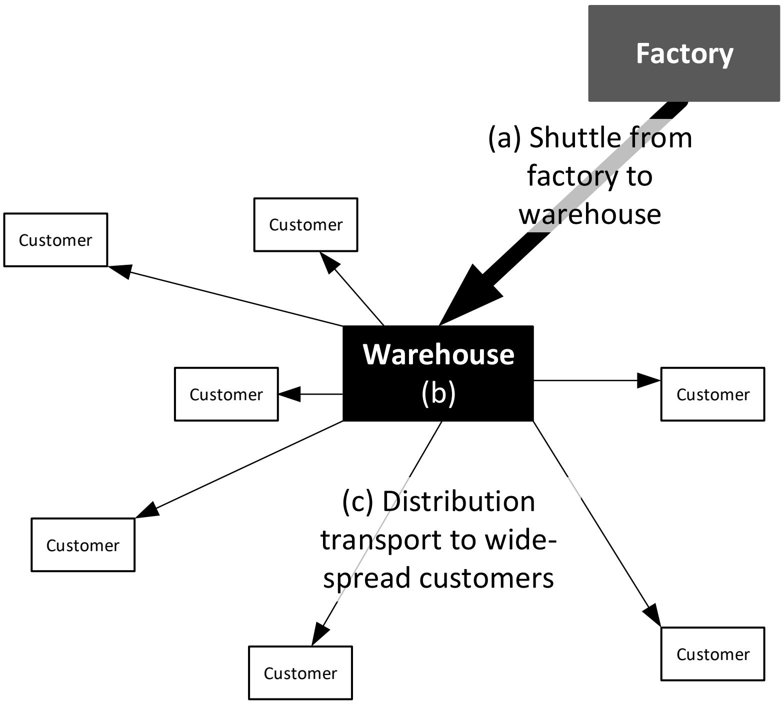

Figure 1: Warehouse distribution processes.

Among the relevant decision factors for the outsourcing company are the following [2, 3]:

- Time and cost for planning, implementing and setting-up the warehouse.
- Cost of operating the warehouse.
- Cost of transportation to and from the warehouse.
- Other aspects such as flexibility, performance or profit margin of the LSP.

This paper is structured as follows: Section 2 shows that traditional warehouse location models ignore important aspects of groupage networks. Section 3 explains the relevance of state regulation and the problem of indirect costs for current LSP pricing models. In section 4, characteristics of a groupage network setting are described. Subsequently, the impact of warehouse locations on transportation times and operations cost are analyzed as well as other influences on LSP pricing. Finally, the paper closes with conclusions and further research areas.

2 TRADITIONAL WAREHOUSE LOCATION MODELS

The following criteria for locating a distribution warehouse only represent a selection of many possibly relevant aspects:

- Qualitative: Proximity to customers, suppliers or competitors, political and legal situation, availability of skilled labor, infrastructure.
- Quantitative: Logistics systems and process cost (e.g. real estate, equipment, wages, taxes, transport and warehousing operations), feasible delivery times to customers.

As many of the criteria are both conflicting as well as non-summable, most traditional warehouse location models focus only on distribution transportation costs [5, 6]. Often, they assume transportation costs that are proportional with regard to volume and/or distance of the source to the related sinks. Other models apply regressive cost formulas to approximate actual trucking companies' pricing structures, which are traditionally based on the declining rates with respect to volume and distance.

- **Shuttle transport**: Traditional warehouse location models neither take into account the shuttle cost to the warehouse nor that from the warehouse to the groupage network hubs.
- **Storing/order picking**: Warehouse operations cost is often neglected, with the models focusing on transport cost only ([5] and [7] for an approach to combine warehouse and transport cost).
- **Distribution transport via groupage network**: Traditional location models focus on the distance between pick-up source (here: factory) and the final customer-drop. However, as will be shown in Section 4, the

distance of the final customer drop from the last groupage network hub is much more important from a total cost perspective.
- **Other factors**: Finally, most models don't consider further important factors for pricing in groupage networks (e.g. specific network structures or different profit expectations etc.).

In a nutshell, traditional warehouse location models ignore relevant aspects of groupage networks. Interestingly, it has also been shown, that under certain circumstances even common LSP price structures are not realistically related to the actual effort and activities involved in such groupage networks [8, 9].

3 TRADITIONAL TRANSPORTATION COSTING AND PRICING MODELS

3.1 Influence of regulation/deregulation on pricing in the LSP market

For a long time in large parts of the Western World, national transport markets were strictly regulated with mandatory minimum road freight rates. For an overview of the historical development of the transport markets see [10-13].

In order to protect state-owned national rail, mail and aviation companies, these rates were artificially high. In Germany, the so-called RKT (Reichskraft-wagentarif), later renamed to GFT (Güterfernverkehrstarif) assumed a declining rate with respect to volume and to transportation distance based on the structure of rail rates. France had the corresponding TRO (tarification réglementaires obligatoires) that was similar, but also included regional postal zone oriented pricing elements.

Due to the high mandatory prices, the mainly small and medium-sized road carriers and freight forwarders had little incentive to increase efficiency. Also, there was no requirement for 'sophisticated' controlling or marketing tools. Therefore, for many industrial and retail companies, it was often cheaper to operate their own trucks, even when half empty.

Since the 1980/90ies, many national transport markets have been deregula-ted, finally resulting in free pricing. The deregulation of the European transport markets showed a gradual abolishment of price regulation, the German GFT became a merely recommended, non-binding reference tariff. However, due to the lack of controlling and pricing expertise, there was a high level of uncertainty among LSPs and customers with regard to pricing. Therefore, for many years, pricing models were typically calculated as 'old Tariff –x%'.

The current situation in the deregulated national transport markets is that there has been a sharp price drop, leading to a consolidation of LSPs. Customers increasingly demand more sophisticated logistics solutions, comprising transport, warehousing and value-added services. At the same time, pricing models are becoming more individual.

3.2 Allocating indirect costs and pricing models in the LSP market

Table 1 shows a classification of transportation service types based on the size of the shipment relative to the truck or container capacity utilization:

- Most costs incurred by FTL (Full Truck Loads) or FCL (Full Container Loads) can be directly allocated to a specific shipment or forwarder.
- LTL (Less than Truck Loads) / LCL (Less than Container Loads) usually bundle shipments from several consignors to several consignees. These can be ‘small’ shipments consisting of individual parcels delivered via CEP (Courier Express Parcel) Services or up to several pallets or loading meters for bulky items via groupage freight.

By grouping LTL shipments from several shippers, LSPs can generate significant economies of scale compared to shipping them individually. However, any bundling of capacities in a multi-user-approach results in a high proportion of indirect overhead costs that cannot be allocated directly to an individual customer drop or pick-up. This proportion increases, the smaller the individual shipment gets. Therefore, calculating LTL prices is more complicated than FTL pricing [14].

Table 1: Transportation service types based on capacity.

Category	LTL / LCL			FTL / FCL
Service type	CEP Services	Groupage freight	Part loads	Full load services
weight per shipment	parcels up to 30 kg	up to 2,500 kg or 5 - 7 pallets	several loading meters or pallets, > 2,500 kg, but less than truck or container	18 - 23 tons, depends on truck / container size
Pricing for regular transports	Pricing based on weight and distance oriented rates		Individual calculation based on return load possibilities	
Pricing for one-off transports	Spot market pricing based on actual costs			

Often, LSP pricing also depends on whether or not transportation needs are regular, occasional or ‘one-off’. Irregular transports are often organized via the spot market and typically based on the available contribution margin, taking into account actual costs and ad hoc return load possibilities [15, 16]. By contrast, regular transports in Germany are often priced based on standard freight rate tables, frequently assuming a declining rate with respect to volume and to transportation distance [6, 17 - 23]. This is possibly due to the fact that customers are used to these price structures and also due to a certain controlling insecurity on the side of the freight forwarders.

Nowadays, further pricing models in practice include:

- Volume or distance rates.
- Relation or postcode-oriented: Fixed rates from certain areas to others.
- Transactional 'flat rates' e.g. per shipment or pallet.
- 'Cost +': LSPs charge incurred cost of their own subcontractors or for their own operations based on an 'open book'-calculation, adding an agreed profit percentage.
- Individual models based on key performance indicators like the number of pallets, shipments, order picks, order lines or delivery performance.

Taking into account the high proportion of indirect costs in groupage networks, the relationship between actual operations cost and the pricing models in the LSP market is not always transparent – neither for the customer nor for the LSP.

4 WAREHOUSE LOCATION DECISIONS IN GROUPAGE NETWORKS

4.1 Groupage network settings in practice

Consider a large groupage freight forwarder with a network of subsidiaries ('hubs'), regularly grouping shipments on pallets over a widespread area, with typical shipment weights of 32 to 2.500 kg. Bulk individual shipments (FTL/FCL) are excluded in the rest of this paper, as well as CEP companies with a high level of automation (e.g. parcel services like UPS or FedEx). (Confer [24] and [25] for an approach to manage bulk shipments, [26] for an overview of the CEP market.)

In a groupage freight network, shipments are picked up from their source (in this paper: warehouse) and are transported to a freight forwarding hub ('pre-carriage transport', see Figure 2). Here, goods are loaded into long-distance trucks for the synchronized line haul transports, connecting the hubs. After reaching the final hub, shipments are delivered to the final customer within the so-called 'post-carriage transport'.

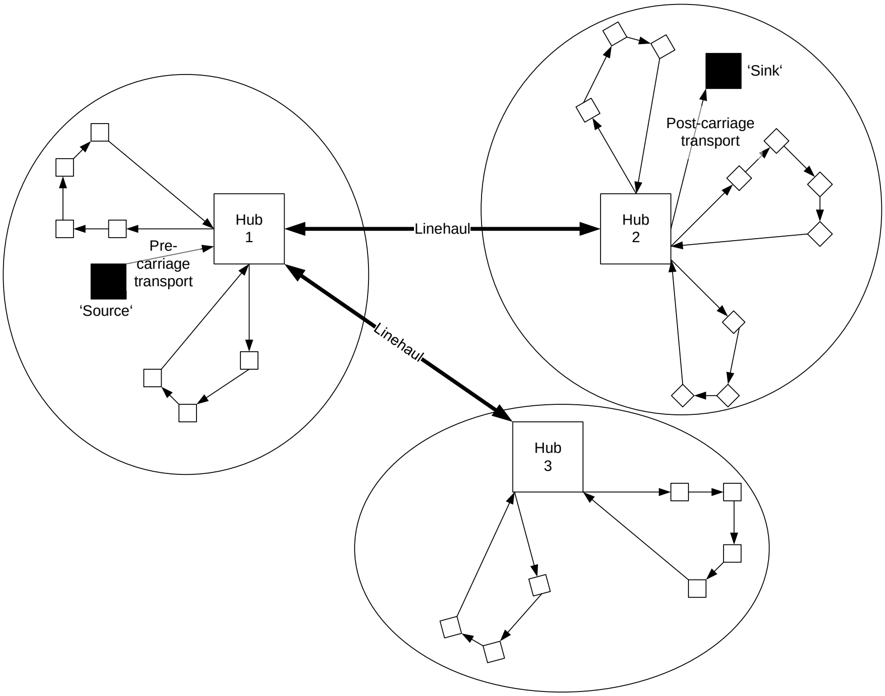

Figure 2: Groupage network structure.

Depending on the type of goods, groupage bottlenecks can include weights, sizes or available pallet spaces. Further restrictions to possible length of tours include the traffic situation, customer time windows or work and rest period regulations. (For an overview of work and rest period regulations cf. [27].)

LSP hubs are normally close to industrial zones with densely distributed pick-up and delivery locations. In some countries, such as France and Italy, a basic declining rate with respect to volume and to transportation distance is assumed; however, it is modified to take into account the differences with regard to population density or industrial infrastructure, resulting in postcode-oriented tariffs. (For the influence of population density on transport costs cf. [28].)

Large German groupage networks include 40 or more subsidiaries/hubs (e.g. DB Schenker or IDS Systemlogistik). On average, this means that every subsidiary has to cover an area corresponding to a radius of approx. 60 km. (For approaches to analytically estimate the average distance cf. [8, 29-32]. All the same, Germany has large industrial zones or other areas with serious traffic jams [33]. Here, maximum distances would typically be less, and the network nodes are more closely knit. In practice, distribution areas of single subsidiaries usually go up to a maximum of 80 to 100 km [18].

4.2 Impact of warehouse location on transportation times and operations cost in groupage networks

In the following, the impact of the warehouse location on transportation cost in a groupage network will be evaluated by analyzing the following components:

- Shuttle from factory to warehouse;
- Shuttle from warehouse to first network hub;
- Line haul transports connecting hubs;
- Unloading and reloading at hubs;
- Post-carriage delivery from last hub.

Shuttle from factory to warehouse and from warehouse to first network hub
Assume that the goods are regularly produced and transported from the factory to the warehouse by FTL. If factory and warehouse are close enough, trucks can commute back and forth several times per day ('shuttle'). Unless the warehouse also stocks raw materials that are required back at the factory, the shuttle truck is unloaded on its return trip.

Increasing the distance from factory to warehouse strongly impacts mileage and driving time, reducing the number of possible return trips per truck and driver. Also, work and rest period regulation may require a second driver per truck, further reducing the number of possible return trips per driver. At the same time, the empty mileage for return trips also increases. Therefore, based only on shuttle cost and time required, the warehouse should ideally be as close as possible to the factory.

The same basically applies to the shuttle transport from the warehouse to the first groupage network hub. Furthermore, if the warehouse is closer to the hub, this enables a later cut-off time for order picking while at the same time maintaining the delivery times in the synchronized network.

Therefore, based on the shuttle cost and time required, the warehouse should also be as close as possible to the hub. Ideally, it would be on the same property as the hub, enabling the latest possible order cut-off times and low transshipment costs. In effect, cost and time for both shuttles imply that the best location for the warehouse is at the hub of the groupage network closest to the factory.

Line hauls connecting hubs and unloading/reloading at hubs
As mentioned, a high proportion of costs are indirect overhead costs with respect to the customer drop. This is especially true for operating and maintaining the line haul networks. Here, costs strongly depend on the regular

routes and the aggregate network flow rather than on individual shipments or even customer drops, thus predominantly generating fixed overhead costs.

If offered for free, the line haul network connecting the subsidiaries would soon be overused. Therefore, transfer prices are required. However, the relation between the fixed and indirect overhead cost and a possible transfer price is not straightforward and subject to the individual LSPs internal profit distribution concept. The line haul costs have to be allocated to the customers, as well [34, 35]. However, they are predominantly independent of the origin of individual shipments.

The overall influence of a customer-specific warehouse location on the line haul operation is, therefore, considered to be low, especially when the individual customer shipments make for a low proportion of total volume in the groupage network [36].

The same basically applies to unloading and reloading at the hubs: Hub location-specific costs and total hub volumes are more important than individual customer shipments. Therefore, the aggregate influence of a specific warehouse location seems to be low with regard to both line haul transports and cross-docking processes at the hubs.

Post-carriage delivery from final hub
Typically, the cost for the pre- and post-carriage LTL-transports comprise between 50 and 80% of total transport cost in a groupage network, depending on network density, transport cycles, service levels, distance from consignee to consigner and the number of hubs involved in the transport flow of the goods [28, 34]. This means that, overall, **short distance transports dominate the network costs**.

Subsidiaries in groupage networks are typically exclusively responsible for the short-distance LTL-deliveries to customers in their respective delivery area. Therefore, post-carriage transports are independent of where the shipments originally came from.

When distributing widespread small shipments, total working and rest time per driver is a key restriction. If the goods are handled on pallets and if they are not exceptionally heavy, it is realistic to assume that there is hardly any difference in the process-oriented costs incurred with regard to the actual pallet weight [21, 37]. Drops that are farther away from the hub than others would, on average, lead to tours with longer first and last ‘legs’ (distance from hub to first and from last drop back to hub). This would lead to less time for additional customers.

In practice, subsidiaries are usually based in the center of industrial zones. Thus, drops that are farther away from the hub not only cause longer tour 'legs', but are also further apart, leaving even less time for additional drops. One way to avoid post-carriage costs that are too high is to reduce delivery areas, e.g. by introducing additional hubs. (For an approach to determine delivery areas cf. [38]).

Take into account that the relevant distance for post-carriage transport is that of the customer drop from the last hub, not the distance between the original pick-up point and the customer-drop. Therefore, the post-carriage transport cost and times are independent of the customer-specific warehouse location.

Overall impact of warehouse location on transport cost in groupage networks
In total, based on the specific LSPs network structure, the **best location** for a customer warehouse location is **directly at the hub closest to the factory**:

- Shuttle cost and time from factory to warehouse are low as warehouse is close to factory.
- Shuttle from warehouse to first transportation hub is almost zero as warehouse is directly at the first hub, enabling forklift or conveyor transports.
- Line haul transports connecting hubs and unloading/reloading at hubs are largely independent of specific warehouse locations.
- Post-carriage delivery transports from last hub are independent of warehouse location.

4.3 Other pricing influences in practice

In reality, transport pricing of LSPs is subject to further influences than transport operations cost, including the following:

- Network structure and total volume;
- Warehouse-related costs;
- Operational efficiency;
- Strategy, profit expectations, and internal cost allocation models.

Synergies based on different network structures and transport volumes can lead to other optimal locations than that closest to the factory. The costs for planning, implementing and operating the warehouse are very individual [2]. They depend strongly on various aspects such as:

- Availability and/or commitment (newly built or rented warehouse);
- Multi-user or dedicated warehouse;
- Technology used (e.g. automated vs. manual, high-bay racking vs. block storage, RFID vs. printed lists etc.);
- The specific customer order picking volume and structure (e.g. how many lines per order, how many picks per line).

The operational efficiency of LSPs may differ from that of their competitors. There could also be strategic reasons for LSP to promote other subsidiaries than the one closest to the factory. Certain subsidiaries may also have different profit expectations and, thus, different markups on their cost. Some might decide to strategically offer their customers extremely low prices (‘bait and switch deals’).

Finally, LSPs have different calculation/cost allocation concepts that may favor or penalize specific shipment structures compared to their competitors. In real-life scenarios, all these aspects can differ strongly from case to case and can cause other locations to be more efficient than the hub closest to the factory. Therefore, these influences need to be assessed individually, complementing the transport operations cost approach.

5 CONCLUSION

This paper argues that based on transportation cost and time, the best location for a national distribution warehouse in a groupage network setting is directly at the hub closest to the factory. This holds for a given factory regularly producing make-to-stock-goods and nationally distributing them to many customers in a ‘few-to-many’-setting with widespread small shipments via a groupage network. It is, however, not necessarily true for the following cases, that constitute areas for further research:

- LSPs strategically promote other locations.
- Both manufacturing and warehouse location are not fixed.
- International distribution including air and/or sea freight.
- Shipment volume that is ‘significant’ compared to the total volume in the groupage network, enabling very different line haul-routes.
- ‘Large’ individual customer shipments (part loads or even FTL).
- Countries with a very different population density and/or infrastructure (e.g. Australia or Chile).
- The case of multiple warehouse locations in a groupage network.

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COMPARISON AND EVALUATION OF SLAM ALGORITHMS FOR AGV NAVIGATION

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Abstract
The navigation technique has been always an important issue for guiding an automated guided vehicle (AGV). With the development of sensor technology, software engineering, and algorithms, there is a spectrum of different navigation methods for AGVs. In order to avoid the additional environmental installation, so as to increase the flexibility of route planning, but to keep the positioning precision, more sensors, such as light detection and ranging (LIDAR), wheel encoders and gyroscope are installed on the vehicles to be automated. Some intelligent algorithms such as simultaneous localization and mapping (SLAM) algorithms and Monte Carlo localization have been developed for the navigation of vehicles, including position and orientation.
The interesting question, especially for the AGV manufacturers, is: which algorithm is more suitable for which kind of applications. The suitability of an algorithm for the navigation of AGVs with facilities of Light Detection and Ranging (LIDAR), encoders and gyroscope is mainly determined by four properties. They are the positioning precision, computational costs, execution time and positioning repeatability. This paper intends to investigate the suitability of an algorithm or a navigation method for AGVs with LIDAR, wheel encoders, and gyroscope. The two aspects of positioning accuracy and repeatability are especially concerned. A general comparison of different navigation methods and algorithms is given. An experimental platform with a basic vehicle, controlling system and sensors is then developed to further evaluate the algorithms. The hardware components and software components are compatible to robot operating system (ROS). This open-source robotics middleware provides services and tools for creating robot applications. As ROS SLAM nodes, open-source SLAM algorithms can be evaluated relatively easily without any rewriting or modification of the algorithms. As a new research field, there is not jet a SLAM algorithm, which is predominant absolutely.

Keywords:
Automated guided vehicle, Simultaneous localization and mapping, Robot operating system, Light detection and ranging

1 INTRODUCTION

Since appearance, Automated guided vehicles (AGVs) have been increasingly applied in production, assembly, warehousing, order picking and etc. The navigation technologies have been continuously developed along with the development of computing and automation technologies [1]. An obvious trend is that the vehicles are equipped with more sensors and therefore can obtain more information of the environment. As a consequence, they may be automatically guided without any support of additional artificial marks in the surrounding environment, such as guidelines or reflectors. In other words, the vehicle is autonomously navigated.

The same as other navigation methods, a main task of autonomous navigation is the path planning for the vehicle. To accomplish this task, the preconditions are that, the vehicle knows the environment and where it is in the environment. These are the two typical problems of mapping and localization, which is named as simultaneous localization and mapping (SLAM). SLAM was first proposed by Smith, Self, and Cheeseman in 1990 [2]. The SLAM algorithm integrates the data collected from various sensors, such as light detection and ranging (LiDAR), inertial measurement units (IMUs), and cameras to calculate the position of the sensor while plotting the perimeter of the sensor.

The environment where the robot is operating is represented as a map. This map should contain enough information to accomplish the tasks of localization and path planning [3]. The main representation methods for a map are a grid-based map, feature-based map, and topology based map. Localization is the problem of determining the pose of a vehicle given a map of the environment and the data from sensors [4]. The pose of a vehicle comprises its location and orientation relative to a global coordinate frame. For localization, a vehicle needs a consistent map and for acquiring a map a vehicle needs a good estimate of the location. SLAM is considered to be a complex problem because of the mutual dependency between mapping and localization [5].

As a hot research topic, SLAM has been received a lot of attention in the last five to ten years for practical applications in the field of robots. There are different SLAM algorithms being developed. Some of them have been published in Robot operating system (ROS) for free access and application. ROS is a Linux-based open-source operating system and a very flexible framework for writing robot software [6]. This system is also used in the paper. An evaluation of the available SLAM techniques in ROS including GMapping, HectorSLAM, KartoSLAM, CoreSLAM, and LagoSLAM with regard to map quality and computational load was given by Santos et al. [7]. GMapping and HectorSLAM these two algorithms are selected in the paper because of the good performance for mapping. Other methods are ignored because of the low map quality. Furthermore, one newly developed SLAM algorithm Cartographer, which is also available in ROS is considered. In all, the paper

evaluates these three algorithms with regard to the suitability for AGV navigation.
The remainder of the paper is organized as follows. The basic working principle of SLAM method and the required components for the vehicles to use this method are given in Section 2. Section 3 introduces the several common and well-developed SLAM algorithms in ROS. Section 4 presents the comparison results. The paper is concluded in Section 5.

2 THE BASIC PRINCIPLE OF NAVIGATION USING SLAM IN ROS

Navigation and positioning belong to the important research part of AGVs. In general, firstly a vehicle needs to establish map modeling by using a laser sensor or a depth sensor, convert laser data in an unfamiliar environment, and then navigates and locates according to the established map. There are also many well-established functions as packages available for direct use in ROS. A framework of the needed functions for SLAM navigation is shown in Figure 1. Based on the explanation of ROS [8], every function is introduced briefly in this section, except for the function of SLAM. As the essential part, SLAM is presented in the next section separately.

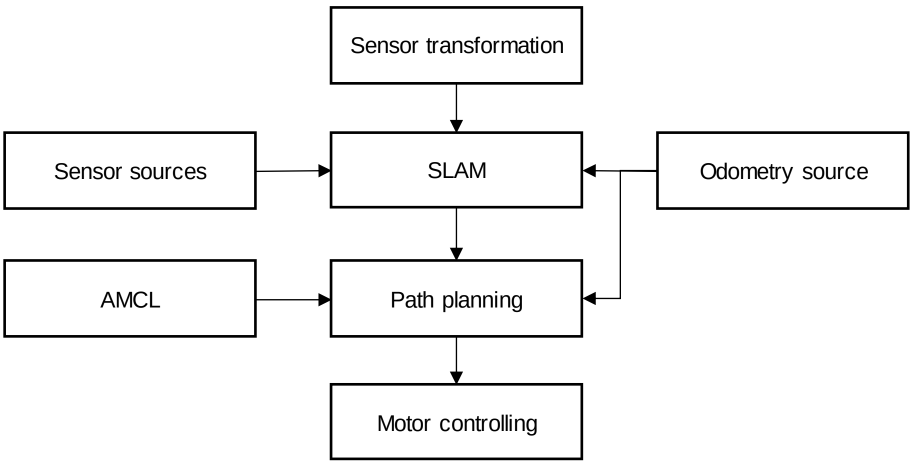

Figure 1: Framework of SLAM navigation in ROS.

Sensor transformation is a component on the robot platform which needs to be provided by users. The aim is to convert the sensor coordinate because the control center of the vehicle is not necessarily on the sensor. The sensor data is converted into coordinate information on the control center. The data acquired by the laser sensor is in the coordinate system of the sensor.

However, the control center is normally the center of the vehicle. Hence, it is necessary to change the coordinates according to the positions of the two origins. In ROS, it is only necessary to tell the positional relationship between these two origins and the transformation can be automatically done.
Sensor sources here refer to the robot navigation sensor data input. Generally, laser sensor data is the input. In this case, LiDAR is preferred. The laser sensor emits a laser beam in a fixed direction, and the emitted laser will be reflected when it encounters an obstacle. The time difference from the transmission to the reception of the laser can be obtained, which enables the calculation of the distance to the nearest obstacle.
Depending on the SLAM method being used, the navigation may require the input of odometry data, which contains the pose and velocity estimations of the vehicle. The pose includes the position and the yaw angle. Incremental or rotatory encoders can be used to appropriately realize the calculation of odometry. However, it is not particularly good and enough, because of wheel slippage in practice. Therefore, it is recommended to use a further inertial measurement unit (IMU) or other sensors at the same time to get more accurate pose information. In addition, ROS uses 1Hz frequency to publish odometry messages. In real systems, it is often necessary to publish faster.
ROS implements the Adaptive Monte Carlo Localization (AMCL) algorithm for the localization of a vehicle based on existing maps. In this algorithm, each pose of the vehicle is represented by a particle and a particle filter is used to track the position of the vehicle. A detailed description of AMCL can be found in these literature [9, 10, 11].
For establishing a map, a proper way to represent the map must be at first defined, for example, a map of the world with latitude and longitude or a map of the subway in a city. As mentioned in Section 1, there are mainly three types of maps being used in the field of robotics. One type is the metric map, which is also named as grid map or occupancy grid map. In the map, each location can be represented by coordinates. Grid map is a map storage method widely used for mapping, localization and even path planning. The package of costmap in ROS is in the form of a grid. The value of each grid is assigned from 0 to 255. Each grid is divided into three states: occupied (with obstacles), free areas (accessible) and unknown areas.
In ROS, there are two components for path planning. One is the global planner, which plans the overall path according to a given target location. The minimum path on the costmap is calculated as the global route. The optimization can be done through the Dijkstra optimal path algorithm or the A* algorithm.
The other one is the local planner, which does evasive route planning based on nearby obstacles. Trajectory Rollout and Dynamic Window algorithms are used to calculate the speed and angle that the vehicle should travel in each cycle. Concrete explanations can be found on the website of ROS [12].
Motor controlling, this function corresponds to the package of “base controller” in ROS. During navigation process, this part is responsible for

packaging the previously derived data into specific line speed and steering angle information (Twist) and publishing it to the hardware platform.

3 SLAM ALGORITHMS

In this section, the three main promising SLAM methods, including GMapping, HectorMapping, and Cartographer in ROS are briefly introduced.

3.1 GMapping

As a laser-based SLAM algorithm in ROS, Gmapping is the most used SLAM algorithm in mobile robots, which needs both laser data and odometry data. It is a highly efficient Rao-Blackwellized particle filter for learning and building occupancy grid maps [2]. Rao-Blackwellized particle filter has been first introduced by Murphy et al. for solving the simultaneous localization and mapping problem [13]. One problem of the particle filter based algorithm is the computational complexity because of the large number of particles for building an accurate map and the other problem is the accuracy of the algorithm due to the particle degradation exhaustion associated with the particle filtering resampling process [5]. The particle degradation exhaustion effect is also known as particle depletion problem and can be found in the literature [14]. Grisetti et al. have developed a proposal distribution, which considers the accuracy of the sensors and enables the algorithm to draw the particles in a highly accurate manner and an adaptive resampling technique, which enables the algorithm to learn an accurate map while reducing the risk of particle depletion [5].

3.2 HectorMapping

Unlike GMapping, HectorMapping is a SLAM algorithm in ROS that builds a map of the current environment in an unknown environment without odometry, which was proposed by Kohlbrecher et al. [15]. It uses the ultra-high scanning frequency of modern LiDAR to estimate the current 2D pose information of the robot. Although it does not provide clear closed-loop capability, it is sufficient for many real-world scenarios [16]. The mapping algorithm has been successfully applied to unmanned ground vehicles, handheld mapping devices and so on. The shortcoming of the hector algorithm is just its advantage because it can work normally by only relying on the laser radar's scanned data. This makes it less effective than multi-sensors. However, it is possible to use Hector algorithm for those robots without odometry information.

3.3 Cartographer

On October 5, 2016, Google announced the launch of an open source SLAM library called Cartographer. Developers can use this library to implement 2D and 3D positioning and mapping capabilities with ROS support [17]. According to [17], the Cartographer mapping and positioning process is similar to the process of drawing a floor plan and positioning in the room, as shown in Figure 2. One person stands in the middle of the room and draws an X on the paper to indicate where the person is. Use a laser to measure the distance of the person to a wall and draw a line on the paper to indicate the wall. Repeat this step for all the walls to see until all the walls are drawn. After that the person moves to the new location since the wall hasn't run yet, measuring the distance to the wall again will determine the new location of the person.

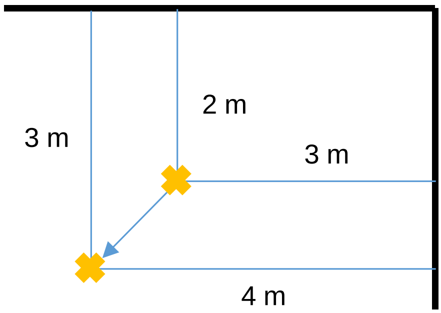

Figure 2: Principle of Cartographer.

A detailed description of Cartographer's 2D algorithms can be found in the paper from Hess et al. [18]. In brief, Cartographer uses Grid to build a map at a 5 cm resolution. There are a certain number of laser scans to construct submaps, which are spliced into maps by submaps. The so-called loopback detection is to optimize the maps of all submaps with a certain number of scans. Local matching is directly modeled as a nonlinear optimization problem. Branch and bound algorithms are used to accelerate the computing scan-to-submap matches for achieving real-time loop closure.

4 COMPARISON OF SLAM ALGORITHMS

Based on the literature and experiments done in the laboratory, a comparison of the three SLAM methods is summarized in Table 1.
To do the experiments, Raspbian operation system and ROS are installed in a Raspberry Pi 3b+. A Laser scanner RPLIDAR A2M8 360° from the company SLAMTEC is used for sensor source of laser scan. Incremental encoders are equipped on driving wheels of the vehicle for preparing the odometry data for ROS. The experiments disclose that it is the easiest to implement Cartographer, the construction effect is relatively stable and the cumulative error is lower than the other two algorithms. With the lower cost Lidar, it is

also possible to examine the method of HectorMappinp. According to the literature, the map resolution can be reached 1 cm by using GMapping [5]. Such high map resolution with stable and good map quality has not been achieved in the experiments.

Table 1: Summary of the three SLAM methods.

criteria	*GMapping*	*HectorMapping*	*Cartographer*
LiDAR Accuracy	Low	High	Low
LiDAR scan rate	No requirement	High than 40 Hz	No requirement
Odometry Information	Yes	Optional	Optional
Computational load	Very high	High	Low
Computational speed	Low	Ok	Fast
Map dimensions	2D	2D/3D	2D/3D
Floor requirement	Even	No requirement	Even
Map resolution	1 cm	5 cm	5 cm
Application environment	Less features or long corridor	No requirement	No requirement
Repeatability	Ok	Not so good	Good

5 CONCLUSION

For autonomous navigation of AGVs with laser SLAM, it is possible to use the three compared SLAM methods. Which SLAM should be used depends on the application environment, the sensors equipped on the vehicle, the position accuracy and so on. In general, it is recommended to use the GMapping SLAM which may reach the highest map resolution for more precise positioning. Of course, there are more requirements for sensors and computational performance of operating and controlling systems. If the precision requirement is not so high, it is then recommended to use Cartographer, because of the lower demand on sensor quality and computational performance. Hence, it is possible to reduce the costs of vehicles. In general, all of the three SLAM methods cannot be used for very high positioning accuracy.

For some applications, it is recommended to have a hybrid of different SLAM algorithms. For example, GMapping can be used to construct the map when the odometry information of the vehicle is normal. If some unusual conditions cause the odometry information of the vehicle to be not normal. Then the SLAM should be switched to Cartographer, so that it is still possible to build the map. If the floor is too uneven and it is necessary to have a 3D map, then HectorMapping should be selected undoubtedly. By judging the different states of the vehicle to select different slam algorithms, the robustness of SLAM mapping can be increased.

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OUTSOURCING RISKS: A CASE STUDY OF THE ELECTRICITY DISTRIBUTION CO. IN IRAN

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Abstract
Outsourcing is a typical strategy adopted to address resource shortage or improve efficiency in organizations. This case is focused on public sectors where decision makers must try different ways to increase productivity. In the current study, the main goals include identification and prioritization of the risks of outsourcing processes in the public service sector of a local Electricity Distribution Co. Firm (EDC) in Iran. This study aims to investigate the risks of outsourcing a process in this company, which can have important effects on the overall goals of the organization. An interview and a study on the background of outsourcing the processes in EDC carried out to identify the existing risks and an impact-probability matrix was built based on collected qualitative and quantitative data. The results illustrate the influence of outsourcing management on all the existing criteria. Hidden costs and financial risks are the most likely risks to happen. Financial risks and low-quality service have the most significant effect on objectives. These results prepare a decision-making support framework for outsourcing risk management plan including risk identification and risk assessment for project managers in this company.

Keywords:
Outsourcing, Strategic decisions, Risk management, Project management, Electricity distribution process

1 INTRODUCTION

Outsourcing services to either an external company or individual contractor have been a widely adopted business strategy to reduce costs. Particularly in the maintenance sector, outsourcing is one of the main strategies to ensure the achievement of expected results and increase flexibility. In this sector, a company adopting this strategy could concentrate on its core activities, get access to skilled expertise or knowledge, and improve the level of service of its end customers. Being the Electricity Distribution Co. (EDC) a public service provider, the business must be run 24/7 because the service should be provided 24/7 for public use. The efficiency of outsourcing and its effects on meeting the goals are investigated and the results affirm the positive influence on gaining objectives [1]. On the other hand can outsourcing strongly improve Risk Management, which is another necessary management strategy to avoid or, at the very least, limit any deviation from the objectives. In fact, outsourcing provides a third party to share any associated risks, therefore reducing the client's burden. However, outsourcing services involve some risks too. This study presents a qualitative risk assessment in which the risks of outsourcing for EDC in Iran are identified and assessed. This can have important effects on the overall goals of the organization.

2 LITERATURE REVIEW

2.1 Outsourcing risks

An outsourcing arrangement needs a clear and practical management plan. As companies focus on improving the efficiency of operations by outsourcing, identifying the scope and goals is critical. Further, avoiding any deviation from the goals is necessary to satisfy all three important outsourcing factors of cost saving, market time reduction, and quality assurance [2]. Belcourt [3] underlines that outsourcing has become one of the most powerful trends in management but that it is also associated with benefits and risks. Quinn and Himler [4] identify three principal risks of outsourcing: to lose the opportunity of gaining capability to perform the function that will be outsourced or develop the wrong capability during outsourcing in the employer company; to lose the interactive capability of research and develop in the employer company; to lose production and marketing capabilities in the employer company; to lose the capability of controlling outsourcing agents. Some scholars believe that an outsourcing contract and its framework has an impact on outsourcing risks. Contracts include clear instructions and comprehensive industrial engineering perspective could help to manage the risks of outsourcing [5]. On the other hand, several studies on outsourcing suggest implementing a risk management plan that should start with the identification of the existing risks in each field, because being specific about the risks could help to manage them more precisely. Examples of this stream of research can be found in offshore outsourcing [6], innovation outsourcing [7], IT/IS outsourcing [8], hotel outsourcing in a tourist destination [9] and logistics outsourcing [10]. A common aspect of these studies is risk identification for that specific field followed by the assessment of those risks.

2.2 Risks associated with the electricity distribution network

From the risk management point of view, there are three kinds of studies in the existing literature on electricity distribution. In the first category, the studies try to address issues about electricity distribution and its impact on the environment and its components, especially humans [11, 12]. The second category includes papers that investigate political issues and decision making [13] often with reference to case studies [14]. The third category includes studies on technical issues [15]. They usually address case studies, some of which are focused on local distribution companies that undertake the responsibility of maintenance [16]. Existing general risk management plans are not satisfactory and when a risk happens, company try to mitigate the negative effects and then enter in the repair phase. The above-mentioned strategy increases the probability of failure in service. It means that local studies should be done to identify and assess the risks in each individual site to support decision making associated with electrical distribution. Because the equipment, maintenance procedure, and even environmental situation of each site are different. To fill this gap the identification and quantitative assessment of risk are necessary. Even if the risk management plan is not a mandatory part of outsourcing contracts in Iran, the study presented here puts forward some elements of interest that could be adopted by companies to improve their decisions. Specifically, a previous work [1] on outsourcing the maintenance activities of a local distribution company in the Mazandaran province (Iran) has been considered as a suitable base to perform a study on outsourcing risks. With all account, outsourcing is a risky strategy, but if a proper risk management model is used, it is possible to take advantage of opportunities besides all risks [17]. Outsourcing is indeed a strategic decision that includes some opportunities associated with some threats, which elsewhere have been called ‘Risky Opportunities’ [18]. In the following sections, the methodology used in the case study will be explained.

3 METHODOLOGY

To collect data a semi-structured interview has been carried out. A set of questions was prepared and asked all interviewees. At the same time, additional questions might be asked during the interviews to clarify and/or further expand certain issues. Data collection has been done during four interviews. For the first interview, the organization's outsourcing expert was selected as the interviewee. After clarifying the research goals, some general information about the company and its duty was collected with open-ended questions. The results of this step enabled the collection of general information useful to continue the literature review. Regarding the results of the literature review, a list of outsourcing risks was collected. As there is not risk management department or responsible, in the next step, the interviewer asked the outsourcing expert to determine the threats associated with the outsourcing objectives based on reports that recorded during previous outsourcing contracts. After determining the organization's outsourcing risks, a questionnaire was prepared for the third interview with the aim of collecting quantitative data on probability and impact of each risk on the organizational goals. The questionnaire includes a Pairwise matrix, Matrix/rating scale and ranking questions to determine the probability and impact of each risk based on the outsourcing history of the organization. During the last meeting, the outsourcing expert was asked to determine the organization's goals for outsourcing, and determine the effect of each of these risks on the organizational goals based on an organization’s background. To provide structured information for supporting decision making, a Risk Impact/Probability Chart was derived from the collected data. In this study, impact shows the size of the effect that varies in terms of cost and influence on the objectives, and the probability of occurrence can range anywhere from just above 0 % to just below 100 %. As the local company did not have a risk manager, the executive manager was chosen for an interview for data collection because he is the outsourcing expert of the company and responsible for outsourcing. Taking part in the survey was voluntary. The respondents’ answers were treated confidentially, and collected data were reported anonymously and in aggregate form. In the following section, the results of the application of the methodology are illustrated.

4 RESULTS

A literature review has been carried out to identify the risks of outsourcing in electric distribution companies [11-25]. The following list reports the major risks that were identified in the review:

Risk 1. Management of outsourcing;
Risk 2. Disaster recovery;
Risk 3. Safety risk;
Risk 4. Financial stability of subcontractor;
Risk 5. Lack of special tools, facilities, and utilities;
Risk 6. Environmental aspects commitment risk;
Risk 7. Operational and transaction risk (Organizational);
Risk 8. Inadequate skills or experience. (System management);
Risk 9. No quality assurance. (Technology);
Risk 10. Human Resource (Technology);
Risk 11. Weak quality of service;
Risk 12. Relative size of subcontractor;
Risk 13. Knowledge transfer;
Risk 14. Compliance risk;
Risk 15. Risks to business continuity;
Risk 16. Ability of the outsourcing company to nurture project loss of the control over the outsourced processes;
Risk 17. Vendor lock-in;
Risk 18. Hidden costs;
Risk 19. Confidentiality of information;
Risk 20. Geolocation risk;

Table 1: Specific outsourcing risks for EDC identified by interview.

Number	Risk	Details
R1	Management of outsourcing	1- Absence of administrative support from the organization 2- Conflict between client and contractor 3- Clear definition of the responsibilities between the organization and the contractor 4- Change in project management
R2	Safety risk	1- Poor definition of specific safety instructions 2- Lack of recognition of the relevant safety standards by the contractor 3- Employees' safety principles are not followed 4- Lack of safe equipment and facilities
R3	Financial stability of subcontractor	1- Inadequate budget. 2- On time payment of contractors' fees
R4	Lack of special tools, facilities, and utilities	1- Complexity of activities 2- Lack of sufficient budget
R5	Operational and transaction risk (organizational)	1- Contract is not clear enough 2- Change in project needs 3- relation between Activities 4- High level of complexity of activities 5- Interference of the outsourced activities with the core activities of the organization
R6	Inadequate skills or experience. (Technology)	1- Complexity of activities
R7	Proper Human Resource (Technology)	1- Lack of skilled manpower 2- Loss of key employees due to internal problems of contractors
R8	Weak Quality of Service	1- Lack of precise definition of the project 2- Complexity of activities 3- Relation between activities 4- Problems in work execution 5- Poor definition of the operation
R9	Compliance risk	1- Sketchy contracts 2- Lack of experience of the contractor in the same field
R10	Loss of the Control over the processes outsourced	1- Control on the scope of outsourced activities
R11	Hidden Costs	1- Complexity of activities 2- Change of the currency conditions during the project
R12	Confidentiality of information	1- Sketchy contracts 2- Lack of sufficient experience of the contractor
R13	Disaster recovery	1- Lack of contractor participation 2- Sketchy contracts
R14	Environmental aspects commitment risk	1- Sketchy contracts 2- Failure to comply with environmental issues 3- Inadequate budget

The list of the risks and sub-risks specific to EDC is illustrated in Table 1. According to the results of the interview and a survey on the history of the events in EDC in Mazandaran, another list was prepared. To increase the level of detail, sub-risks for each risk were defined. Being specific and specifying elements of each risk as a sub-risk list, help to estimate the impact of each main risk on the objectives. A rough estimation of the probability of occurrence of each risk is identified according to the experience of the outsourcing experts. This data is used for making the probability-impact chart for the risks in EDC that is shown in Fig. 1. Paul Newton suggested a scale of the probability-impact matrix in 2015 that is used as a reference index [26] in this study (see Fig.1). Using this scale, risks classify regarding two indexes include the impact of the risk on objectives and the probability of happening of the risk. The more impact and probability, the more important to pay attention to that risk. Regarding this scale, it is possible to categorize risks in five categories include minimal risk, low risk, moderate risk, high risk, extreme risk. The scale is known as probability-impact matrix and it is one of the most popular quantitative tools in risk assessment.

Impact Probability	Negligible-1	Minor-2	Moderate-3	Significant-4	Severe-5
>81%	Low Risk	Moderate Risk	High Risk	Extreme Risk	Extreme Risk
61-80%	Minimal Risk	Low Risk	Moderate Risk	High Risk	Extreme Risk
41-60%	Minimal Risk	Low Risk	Moderate Risk	High Risk	High Risk
21-40%	Minimal Risk	Low Risk	Low Risk	Moderate Risk	High Risk
<20%	Minimal Risk	Minimal Risk	Low Risk	Moderate Risk	High Risk

Figure 1: Risk probability-impact scale [26].

5 DISCUSSION AND CONCLUSION

There are four main risk response strategies and decision makers choose one or a combination of them to deal with a risk according to the result of risk assessment. These strategies include acceptance, mitigation, avoidance, and transfer. In this study, the probability-impact matrix is used to evaluate the level of the risks and, considering the result that is shown in Fig. 2. The probability-impact matrix of outsourcing jobs in EDC shows that there are 3 risks with high importance, 5 risks with moderate importance, 4 risks with low importance and 2 risks with minimal importance. This matrix is a tool to support decision making for the best response strategy for each risk according to its category. In the following sections, the different risks and the best response strategies for them will be discussed. EDC has different activities that are outsourced. They have several subcontractors to do outsourced jobs that are already up for auction. This company has approximately between 20 and 25 auctions to outsource different jobs. Forty-five local subcontractors compete to take the job, but there are seven subcontractors that usually win the auction. The following information shows the condition of all of the contracts and sites belong EDC.

Impact Probability	Negligible	Minor	Moderate	Significant	Severe
≥81 %			R3		
61-80 %				R11	
41-60 %			R8		R1
21-40 %		R12	R9,R10	R4,R5	
≤20 %	R14	R13	R2	R6,R7	

Figure 2: Risk probability-impact chart for local EDC.

5.1 Minimal risks

Disaster recovery and environmental aspects commitment risks have minimal importance in this company. It means that, in this location, subcontractors have been committed to environmental conservation and in the case of disaster, the subcontractors had good cooperation and commitment.

5.2 Low risks

Confidentiality of information by local subcontractor has low risk. Therefore, it should be considered and monitored because still there is a risk about information. It is crucial to protect the organization's important data and intellectual property. Safety risk has also low level. It shows that contractors are taking care about the safety of the personnel and follow safety instructions but as the safety of staff has high priority, the safety instructions should be obligatory and controlled. Compliance risk has a low level of importance too. It shows sub-contractors have been committed and suitable for the second level of subcontracting jobs. According to the literature and case studies, the most important risk in this group is losing control over the outsourced processes. However, the results of Fig. 2 suggest that local companies are willing to cooperate with clients. This group includes acceptable risks that can be tolerable with a scheduled monitoring and reporting system.

5.3 Moderate risks

Fig. 2 shows that moderate risks include inadequate skills or experience, proper human resource, operational and transaction risk, weak quality of service and a lack of special tools, facilities, and utilities. It seems that the root of all these risks is weakness in project management. Human resource management could be the key solution of the technical problems and unskilled personnel. Better project planning and work breakdown system could clarify the relation and sequence of jobs and the necessary facilities and utilities. Therefore, project planning can avoid operational and transaction risks and lack of special tools, facilities, and utilities. Setting up quality control and quality assurance system can solve the service quality problems. According to the PMBOK, human resource management and project planning and leadership are two of the main duties of the project manager [27]. This group of risks is not acceptable, and the existing effects should be mitigated and the risks should be avoided. To sum up, the risks with moderate importance in this company has root in project management weaknesses and the above-mentioned issues should be considered to avoid any deviation from the objectives.

5.4 High risks

From the risk management point of view, this level of risks has high priority and they should be transferred or avoided. Management of outsourcing in EDC Company has a high level of risk. It contains different elements and the risk derived from weaknesses of the client's management. Therefore, project management should be responsible for this risk. On the other hand, financial stability of subcontractor and hidden costs of outsourcing could be tackled by a good contract and the selection of proper subcontractor. Again, the role of project management is key in solving the problems of existing and future contracts. To sum up, outsourcing in EDC, is the most effective way to address high and moderate level risks in EDC is to fortify project management and risk management.

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DIGITIZED PLANNING WITH VISUALIZATION FOR WAREHOUSE LAYOUTS

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Abstract
In warehouse planning and dimensioning, many parameters and conditions have to be met and goals must be fulfilled, e.g. labor and investment costs, desired throughput and capacity, available material handling technologies and size constraints. These factors determine the ultimate choice of a particular alternative from a wide range of solution alternatives.
On the one hand, the warehouse planning process is very complex and takes into account all different aspects of decision-making. On the other hand, it is expected that the planning period is shorter and shorter. To balance out the competing interests of accuracy and time, it is a promising approach to make use of computer-based planning tools. They can be used to find the most cost-efficient alternative and to visualize its layout.
In addition, at the end of the planning process not only technologies and layout dimensions are specified, the warehouse layout with the rack configuration, the conveyors and the buildings should be visualized in three dimensions.
It is a promising approach to integrate the detailed layout drawing through computer-aided design tools such as AutoCAD Inventor into warehouse planning process. Software is developed for detailed warehouse planning. The core modules of the software can generate a favorable warehouse alternative and an AutoCAD-Add-On for the visualization of the outcomes.
With the planning tool, the planning period can be significantly shortened while simultaneously the planning quality, especially during the period of rough planning, increases. To balance out the competing interests of accuracy and time, it is a promising approach to make use of computer-based planning tools. They can be used to find the most cost-efficient alternative and to visualize its layout.

Keywords:
Warehouse planning, Layout configuration, Labor and investment costs

1 INTRODUCTION

A designing engineer needs to face a lot of challenging tasks in warehouse planning [1]. For example, many data as influencing factors must be collected,

alternative warehousing technologies must be evaluated, conveyors for supply and disposal must be planned and so on [2, 3].
Due to commercial competitiveness, warehouse planning must be done in a shorter and shorter time period [4]. Simultaneously the planning quality must increase and contractors are not willing to pay a higher price [5]. The dilemma can be solved by integrated and computer-based planning tools. The designing engineer is disencumbered from routine activities and can put his focus on creatively searching innovative solutions. These are the main motivations for us to develop an integrated computer-aided tool.
In the literature, there are also some contributions in the field of layout planning. Jiang and Nee [6] present a novel factory planning system for real-time on-site facility layout planning, in which augmented reality is used to provide visualization of the layout process. Mowrey et al. [7] formulate warehouse rack layout problem to maximize exposure. A digitized decision-making system based on AutoCAD is developed for warehouse area planning and construction [8]. Koehler et al. develop two algorithms for creating warehouse models, which can be used to optimize a warehouse layout [9]. Dias et al. [10] integrate CAD and simulation in one system for facility layout and production process optimization.
In the market, there are already some commercial software tools, which assist warehouse layout visualization and simulation, such as CLASS, Sketchup and so on. There are also AutoCAD drawings of different rack systems which are available on the internet for free use. These contributions avoid in each case the work of racks layout construction from zero. However, the drawings cannot be modified automatically or manually with very less knowledge of AutoCAD.
The remainder of the paper is organized as follows. In Section 2, the main influencing factors to be considered during planning a warehouse and the main phases included are at first introduced. Section 3 presents the computer-aided tool including planning algorithm, concept decision, storage layout configuration and visualization of racks layout. Section 4 gives a short conclusion of the paper.

2 PLANNING OF WAREHOUSE SYSTEMS

The planning of warehouse systems is done in phases and must consider a range of influencing factors.

2.1 Phases of planning a warehouse system

The first step in planning a warehouse is to undertake a condition analysis, as shown in Figure 1. The relevant information about the actual situation is recorded as well as the desired state after putting into operation the new warehouse. Additional information about the article stock, article stock changes and order profiles have to be collected and evaluated. This information can often be inquired of existing databases.

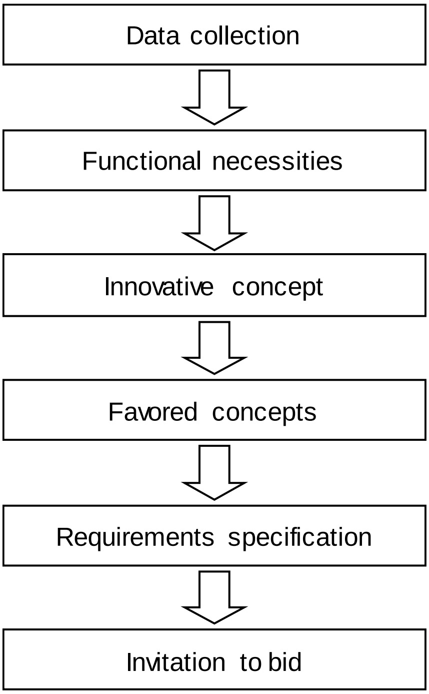

Figure 1: Steps in the planning process.

The next step in the planning process is the definition and documentation of the functional necessaries. This documentation should be manufacturer-neutral and technology-neutral. It should describe in an abstract manner the functions and outputs the new warehouse has to fulfill. Usually, each warehouse is a unique and singular solution and so the outcome of this step is the so-called innovative concept. It contains the solution approaches, which build the basis for the further planning. Herewith several absolutely different systems can compete for realization. A dimensioning has not been done and so a calculation and thus comparison of the concepts cannot be attempted at this stage.
In a next step, the found innovative concepts are compared and evaluated. One or more favored concepts are now specified in a detailed planning step.
The requirements specifications are given to possible contractors and they are invited to bid. The planning process ends at this point. The next steps are the selection of a contractor, setting up a treaty, realization and putting into operation. The smooth advance of these steps heavily depends on the quality of the planning results and thus the importance of the planning process should not be underestimated.

2.2 Influencing factors

Influencing factors can be roughly grouped in direct factors and derived factors. Direct factors are provided by the principal. These factors are requirements which have to be met by the warehouse to be designed. Direct factors are among others:

- geometrical dimension of the building ground;
- maximum height of the building;
- needed capacity;
- demanded output;
- maximum investment;
- maximum operation costs per period;
- given by legal requirements.

The derived factors are calculated from the direct ones or needed to compare alternative warehouse solutions. In most cases, derived factors are performance data or characteristic values of a special solution. Examples of derived factors are:

- cycle time;
- measures of the actual warehouse;
- price per storing position;
- return on investment and
- operation costs.

Both, direct and derived factors are needed and used to compare and value the later solution. Thus, they must be defined independently of the solution.

3 APPROACHES OF SUPPORTING THE PLANNING PROCESS WITH COMPUTER AIDED TOOLS

The described planning process is a complex fastidious process. Without support from computer-based planning tools, it heavily depends on the experience, the carefulness, and exactness of the designing engineer. To reduce this dependence, a computer-based planning tool for warehouses was developed. It releases the designing engineer from routine activities and enables the engineer to focus on innovative concepts and creative tasks. Additionally, the tool is suitable to shorten the planning time. The tool automates the steps of dimensioning, calculation of output, investment and operating costs and rough visualization. It supports the designing engineer in choosing the solution that suits the requirements best.

3.1 Structure of the program

The program is structured into three parts. The parts are a user-interface to input the necessary data, the planning core which actually computes the solutions and which is split up into loops and finally a visualization part which

presents the results in a three-dimensional form with the help of a computer-aided design program. The program used for this task is AutoCAD by Autodesk, Inc.
The interaction between the user and the program is kept as simple as possible to open a wide range of application. In the beginning, the user is asked for some basic data (Figure 2) by means of forms. They are

- the storage and retrieval system, e.g. an automatic storage/automatic retrieval system or a very narrow aisle stacker;
- the dimensions, weight and storage direction of the palettes;
- the building type, e.g. wall-roof-mounted or a classic concrete building;
- the dimensions of the building ground and the maximum height for the building;
- the fire security segments and their maximum dimensions and the sprinkler system needed;
- the needed capacity;
- the average and maximum output and
- the working shift system employed.

All these data are used to calculate the warehousing concepts that observe the requirements. The valid concepts are then listed and can be classified by either capacity, investment, operation costs or any rate of these factors, e.g. investment per palette storage unit.
The designing engineer now can choose one of these concepts and the program visualizes it as a regular AutoCAD-representation.
Additional to the input data that changes with any new planning project some basic data that are persistent during some planning projects are kept. This persistent data is, for example, the price per storage unit, the security allowances per aisle or the operation costs per hour of employing a very narrow aisle stacker. All data, the input data as well as the static data together with the visualization files from AutoCAD Inventor are stored together and build a project history. This helps to document the planning process and can help to give reasons for the actual planning result at the end.

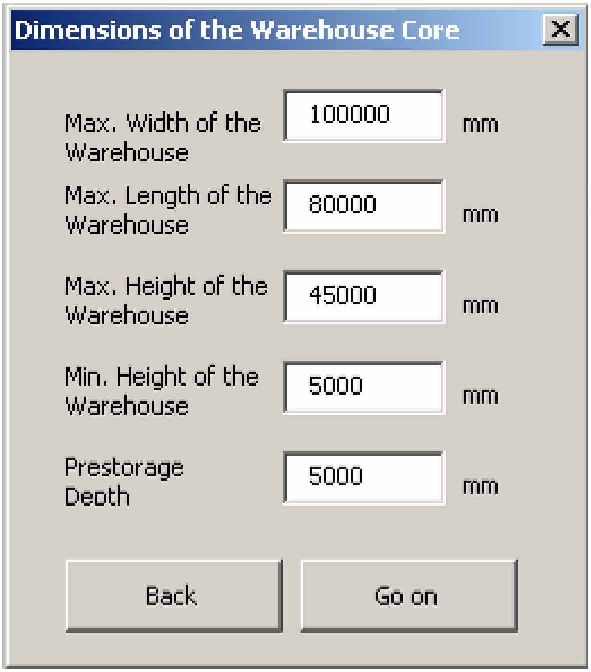

Figure 2: Input window for dimensions of the building (example).

3.2 Planning algorithm

The planning algorithm is divided up in an outer and an inner loop. The outer loop is divided up into three sub-loops, one for each dimension of the warehouse core. The first dimension varies the length, the second varies the width and the third varies the height. The variation interval for all three sub-loops is from zero to the respective dimension of the building ground and the maximum height, all given by the user.

The warehouse is divided into elementary cells by the program. One elementary cell is the smallest unit by which the whole warehouse can be composed. The dimension of this elementary cell is the length, width, and height by which the dimensions of the warehouse are increased in each loop. The three sub-loops guarantee that all possible warehousing core dimensions are taken into account.

The inner loop is a sequence of several calculations that compute the characteristic factors for a specific warehouse given by the outer loop. The factors calculated are

- number of levels and aisles and length of the aisles, derived from the actual dimensions;
- capacity of the warehouse, derived from the number and length of aisles and levels;

- dimensions of the building, derived from the warehouse core and added an allowance for e.g. the sprinkler system, walls, security areas;
- cycle time and the output derived from it;
- investment, split up into investment for the building, the storage system, and the storage technique and
- operational costs split up into depreciation, maintenance, labor costs, and capital costs.

In a first step, all solutions that have a capacity or output lower than required are discarded. The remaining solutions are internally stored with their respective dimensions and the enumerated factors.

3.3 Concept decision

The result of the calculation activity of the tool is a list of alternative warehousing concepts. It is the designing engineer's task to select one or more solutions for further consideration. The tool analyses the operating costs of the selected solution variants for the designer's reference (Figure 3).

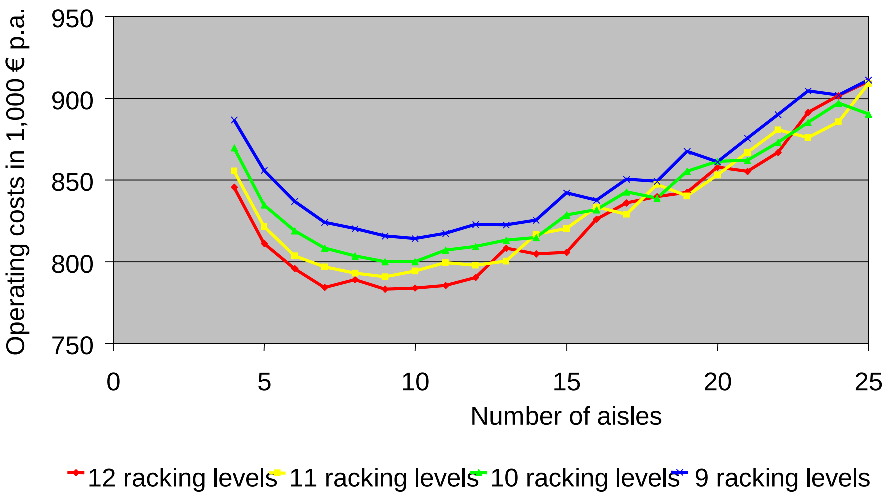

Figure 3: Comparison of solution variants with regards to operating costs.

The designing engineer's task is supported by a group of index numbers. The results can be sorted by the height of the investment, by the annual operating costs, by the price per pallet place or by the maximum output of the actual warehousing system.

Once the designing engineer has chosen his preferred solution, either one or many, his further work of fine planning is supported by a visualized representation of the selected warehousing solution.

3.4 Visualization

The selected warehousing solutions are transferred into a three-dimensional computer-aided construction tool Inventor. The tool used is AutoCAD, but the resulting DWG-files are inter-operational and can be understood by other CAD-tools as well (Figure 4).

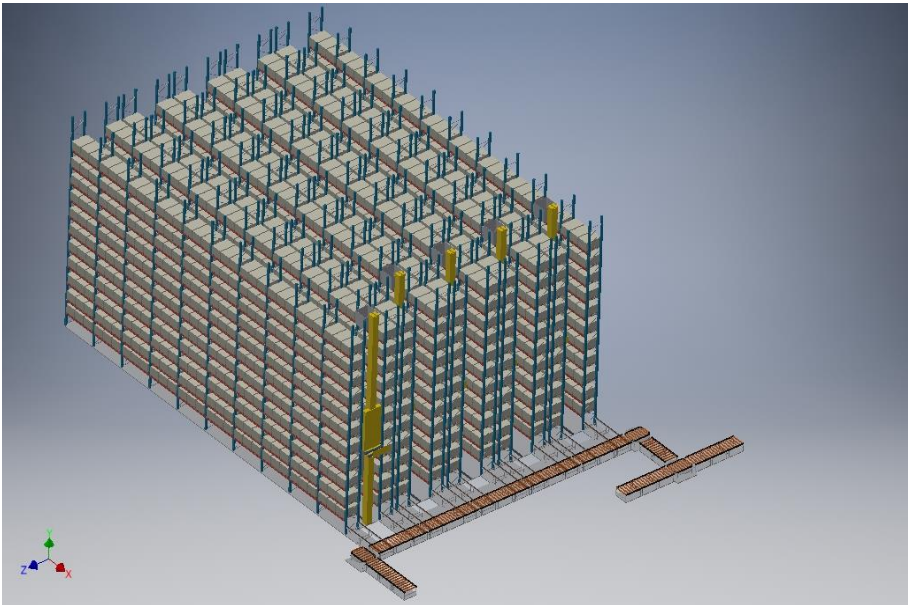

Figure 4: Warehouse core with peripheral components.

The steps in visualization are the compilation of the data needed for constructing the warehouse, the translation of the data into three dimensional coordinates, the placement of the warehousing solution in the environment of the 3D-CAD-tool, the actual drawing of the model and if necessary the integration of the model into already existing building and conveyor systems. The compilation of the needed data is done by the planning tool. It selects all the data like the dimension of the building, the loading units or the shelves, the number of aisles and the stacking height, the prestorage area and writes them into a datasheet of the Microsoft Excel spreadsheet application. Microsoft Excel was chosen as the transfer file format due to its wide

spreading. Additionally, it is easily readable, not only for machines and thus the results are easily editable even without running the planning tool again.
With the given data the visualization module of the planning tool calculates the coordinates of each pallet place, shelf and the building itself. Given the security distance between shelves and building and the aisle width, it can place the shelves in the building. Furthermore, it places the prestorage area relatively to the warehousing core. Then it has the coordinates for a three-dimensional representation of the planned warehouse. With interfaces provided by AutoCAD, it can transfer these coordinates into the 3D-CAD tool, which draws the model.
As the next step, the designing engineer is asked to place the warehouse in the coordinate system of the 3D-CAD tool. Then the designing engineer either has a foundation for further fine planning steps or he has to connect the already planned components, like conveyors or other buildings to the warehouse core.

4 CONCLUSION

Computer-based tools supporting any kind of planning process have reached a wide spreading. They support the construction and customization of any technical device. Without an obvious reason, the planning of warehouse systems is not widely supported by computer-based tools yet. The introduced computer-based planning tool closes this gap. It helps to reach the most crucial targets that occur in planning nowadays.
It helps to keep the time for a planning cycle low whilst it also raises the quality of the planning result. The results offered to the designing engineer take into account any available alternative considered in the computer-based tool. Thus solutions preferred by the designing engineer can be overruled by economically more reasonable results.
It is an important task for further developments to build computer-based tools surrounding the actual tool. A modular construction is an important requirement for these tools. Modularity in this context opens new abilities for singular solutions to interact with each other.
The actual tool is build up by two modules, the planning module and the visualization module. Other modules can be easily attached to the now found solutions. For example, modules that plan the prestorage area or support the fine planning process are needed as a next step.
The next research aims are to develop a self-learning assistance system for the planning tool. It should capture the reactions of the planner, the resulting process steps and solution steps on the way to the optimal warehouse design and convert them in machine learning algorithms.
On the one hand less experienced planners can share this knowledge and on the other hand, the work with the planning tool can be considerably shortened.

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SESSION G
Management Practices and Methodologies

SMART PRODUCTION
A PARADIGM-SHIFT IN THE FIELD OF MAINTENANCE

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Abstract
A paradigm shift in the field of maintenance is essential for companies due to a progressive digitalization of production processes. Therefore, the new paradigm considers all phases of a system, from procurement, operation through to the recycling of the machine. Initially, at the start of the cycle manufacturers of machines and equipment have to focus on design, implementation and quality assurance in compliance with the requirements for operation and maintenance to minimize lifecycle cost. During operation, an efficient strategy for maintaining must be defined. Based on the introduced paradigm a maintenance check is presented, able to provide orientation to small and middle-sized enterprises regarding their maintenance situation and level. The respective level is described on basis of the degree of maturity. Regarding further steps, it is the fundament for strategic decisions and activities.

Keywords:
Maintenance 4.0, Smart production, Maintenance check, Maintenance maturity

1 INTRODUCTION

Referring to increasing worldwide competition regarding production costs, for industrial enterprises process accuracy and efficiency become more and more important. Therefore, different management strategies focus on the reduction of all kind of losses within production processes. For example, Lean Management defines seven types of wasting and tries to avoid them. On the other hand, TPM (Total Productive Maintenance) has the objective to increase OEE (Overall Equipment Efficiency) as much as possible. Especially, the machine availability is very important for such a performance index. For this reason, several maintenance strategies have been developed and adapted for an optimized machine performance.
More and more automatization and digitalization, as well as an increased number of crosslinked machines within the 4th Industrial Revolution, implicate new requirements and demands, especially for current maintenance strategies. Against this background availability of machines and devices within production lines and systems becomes more and more important.

Therefore, importance regarding the economic management of tools and machines increases continuously.
Nowadays companies aren't often aware of the status of their maintenance situation. In many cases, the key performance indicators necessary for the evaluation of the maintenance level are not defined. Additionally, data for the measurement of machine conditions or the efficiency of maintenance measures are not available. At least methods and algorithms for analyzing and evaluation are missing. For that purpose, small and middle-sized enterprises struggle to define adapted maintenance strategies for their company. This situation is intensified by upcoming activities of the 4th industrial revolution. 'Industry 4.0', 'The Internet of Things' or 'The Industrial Internet' generate a completely new maintenance situation, defined as Maintenance 4.0. Figure 1 shows several influence factors shifting needs of current and future maintenance strategies. Demands like just in time production, smaller lot sizes, more flexibility have to be faced by the maintenance departments.

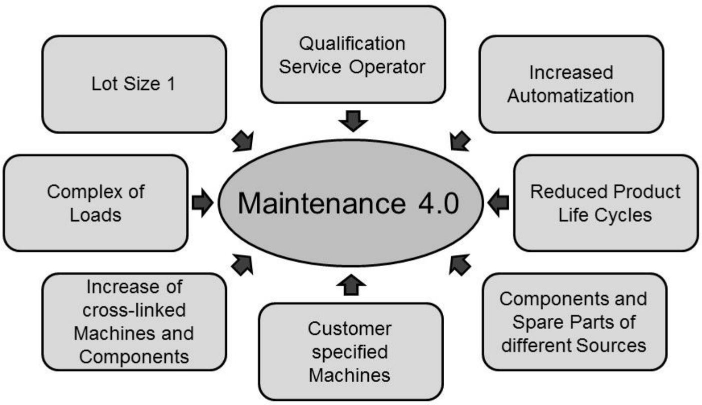

Figure 1: Maintenance influenced by Industry 4.0.

Thus, rising machine complexity and an increased number of integrated systems lead to a degradation of the performance of maintenance workflows. But, due to a large number of integrated sensors, a monitoring of systems and a prediction of their behavior is getting much easier. Therefore, a digitalization of production offers a lot of new opportunities combined with several new requirements and demands.
The following report presents an approach to give future maintenance a new structure. For the evaluation and the control of maintenance activities, a maintenance quick check was developed and is presented within this document.

2 RETHINKING MAINTENANCE - NEW PARADIGM

The easiest way to make operation and management of technical equipment more efficient for a company would be to stop doing maintenance. This approach is simple and is often offered by consultants, but the long-term results are usually very costly. In literature, the term “maintenance strategy” is typically associated with three types of maintenance: predictive, preventive and corrective. John Moubray is one of the authors firstly gaining the full significance of maintenance for the success of a company [1]. During his work as a maintenance manager, he identified fifteen key areas of maintenance management which should be used by the executive staff for reorganizing a company. Thereby, the goal is to find an appropriate maintenance strategy to reduce overall expenditure and total life-cycle costs [2, 10]. Moubray is convinced that each of his proposed key areas on its own makes an important contribution for all professionals working in the field of maintenance. Therefore, he noted that the defined areas together set up a whole new paradigm of maintenance [1]. If all aspects of this paradigm shift should be fully implemented, the work organization and the workflows of a company have to be completely rethought or at least reorganized especially under recent developments in the field of smart production.

The internet of things, on one hand, leads to new and higher requirements regarding technical complexity and cross-linked-systems on the other hand condition monitoring and big data support the required changes in the field of maintenance effectively [3]. Predictive maintenance becomes the first catchword by promoting new technical approaches which will support reorganization processes in the field of maintenance. In view of these developments, six key areas (see Figure 2) focusing the paradigm of Moubray are defined in order to help management of small and medium-sized companies in analyzing the current situation and to derive first steps of a re-organization of their maintenance situation. The selection of the six key areas out of Moubray’s fifteen is based on the results of a workshop with company representatives. Figure 2 illustrates the relevant key areas for a maintenance department in future: Machine-design, Data Management, Costs, Strategy, Organization, and Personnel Management.

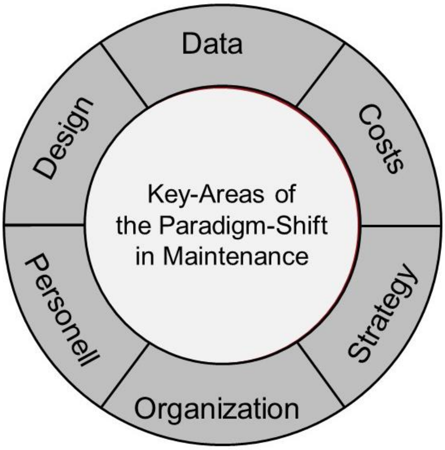

Figure 2: Key areas of paradigm.

2.1 Key area "Design of equipment"

When dealing with the maintenance of technical equipment the basis for all strategies and service activities is the design of the machine [4, 6]. Nowadays constructing engineers often define functionality, structure, and design completely themselves without any discussion with the service department regarding operating, maintainability and life cycle of the machine. In practice, the maintenance workforce often accepts the given structure and technical functionality of an existing technical object. This is the case, no matter how complex and burdensome the implementing of a maintenance task is. Even more, it is critical if construction departments design machines with defined weak points in order to push spare part and service business or the replacement of the equipment. Maintenance departments mainly complain about the frequency of failure due to product development without any consideration of service activities or machine lifecycle. In most instances no changes at the machine are initiated by the maintenance department nor are they economical. Subsequent amendments at the machine often are very expensive or mainly impossible. In such a case a higher quantity of maintenance orders or improved work instructions cannot solve the problem. For future projects in the field of production system development, it must be ensured that the most of the maintenance problems are avoided or eliminated at the planning stage [1]. Therefore, the management of the producing enterprise has to define and control the implementation of a design standard for new machines. These requirements have to be fixed together with the machine producer within a specification contract. This can include modifications of the asset and the operating procedures but it could also lead to lower demands of the management regarding the outcome of the system.

Effectively, both partners discuss the necessary functions as well as the pros and cons of the machine collaborative. Such negotiation should be carried out with the participation of maintenance department and service operators. Therefore, equipment designers have to work together with the maintenance staff who take care of the equipment later on. The task of such a team is to develop equipment which must fulfill the desired purpose and work, but they have also to consider what must be done to keep it running.
Especially in future projects that require not only a high availability of the machine but furthermore demands like safety, environmentalism, low energy-consumption, high and stable quality standards and last but not least low life-cycle costs of the machine a close cooperation between supplier and customer is mandatory. Topics like spare part management, energy consumption as well as service support have to be discussed, calculated and fixed. For new machines following Industry 4.0-Standard, it is of vital importance that the data management is described in detail, which will be considered in the next chapter.

2.2 Key area “Data management for maintenance purposes”

First, it has to be mentioned that collecting data for maintenance purposes is an unnecessary expense, because data is only collected and analyzed since failures or inefficiencies are not prevented [1]. As a result, the validity of data must be further reinforced with the objective to identify the failure pattern which applies to each of the failure causes. A collection of data on error classes without stating the possible causes allows no sensible actuarial analysis. Furthermore, data collection currently often has a sporadic and not continuous character. Therefore, in practice, databases at many times are incomplete and do not allow precise fault analysis. Additionally, information is not prepared in real time and have a general, not failure specific character. Complex correlations between different data packages often cannot be identified due to unsuitable tools and missing knowledge.
Yet today, data for maintenance purposes in a company are usually oriented towards the past and not towards the future. Therefore, the management often pays attention to problems that have already arisen. The intention is that a dashboard with data regarding the progress of failure and abnormalities indicates the future wear behavior. Especially trends following Industry 4.0 pronounce condition monitoring systems and promise precise wear simulation and transparent machines offering all relevant data in real time [3]. In the best case, maintenance decisions are proposed by this system before the failure occurs and have to be implemented by the management. This strategy is not able to prevent machine breakdowns completely. At least only failures already established in the past can be avoided. For that reason adapted maintenance strategies referring to different failure classes have to be developed.
Moubray considers that the management has to get comfortable with the idea of uncertainty regarding the forecast of failures in the field of maintenance [1]. Especially trends like individually designed machines, shorter life period of

future equipment, different workloads and higher complexity due to an increasing number of components and interdependencies lead to a reduction of comparable and evaluable data. To reach the desired level of efficiency individual maintenance strategies for each machine and company have to be defined in order to deal with uncertainty confidently. In consequence, if the uncertainty cannot be reduced to an acceptable level, the effects of failures have to a certain extent diminished or corresponding workflows have to be set up to deal with the consequences. Accordingly, a maintenance strategy adapted to different kinds of failure classes has to be developed.

2.3 Key area "Costs"

If managers are asked what are their objectives regarding maintenance, they often mention an optimal solution for the tradeoff problem of simultaneously maximizing the plant availability (machines and production lines) and minimizing maintenance costs (operators, spare parts, service, etc.). Costs for maintenance known as a large proportion of total expenditure of a company have significantly risen of during the past few decades [1]. This leads to more attention of managers to set up cost-cutting programs in the field of maintenance. In most cases, only initial investments for machines and devices are focused while total lifecycle costs are neglected [3-5, 8]. Regarding the monitoring of maintenance costs mostly direct costs for spare parts or service effort are controlled. Indirect maintenance costs for machine breakdowns or quality losses as well as increased energy consumption currently are not measured and analyzed [10, 11]. Consequently, many small and middle-sized enterprises do not know their indirect maintenance costs. In consequence, they are not able to take them into account in order to reduce the overall maintenance costs for their company.

For future cost reduction programs, this is clearly the wrong approach especially with focus on future-oriented smart production which has a wide range of additional objectives [9]. Smart production means that strongly connected devices interact together to realize a flexible and an efficient production under current conditions. If the concept of smart production is fully implemented, a significant increase in added value and a reduction of production costs will occur. But, a result of growing information technology within a production system will cause a rising number of failures. At the time as the production will be heavily influenced by connected components and machines which autonomously control the production processes, the management has to accept the costs to own, to operate and to maintain these highly complex systems. Therefore, if a smart production concept is able to generate a maximum return on investment, the management must set up a binding standard for maintenance for keeping the system working efficiently for a planned period. It appears clear that implementing a smart production will lead to an increasing role in preserving all aspects of the physical, financial a competitive health of the production system. New approaches like Asset-Management try to evaluate machines and equipment regarding all technical and financial aspects permanently using all expertise available in the company [8, 9]. This strategy is described by Moubray, who defined maintenance as a continuously, proactively and directly issue, rather than situational actions due to errors or when time permits [1]. Therefore, the management has to define a maintenance standard to reach planned production costs for each unit. These costs include the expenses for all maintenance purposes along the life-cycle of the production system. Also, direct as well as indirect maintenance costs have to be taken into account. In order to minimize costs continuously, the defined standard has to be analyzed permanently and optimized for the a priori defined efficiency of the production system.

2.4 Key area "Maintenance strategy"

In literature, the term "maintenance strategy" is typically associated with three types of maintenance: predictive, preventive and corrective [1, 3, 4, 6, 8]. A predictive course of action examines the likelihood that a failure will occur in near future. These data are utilized for scheduling maintenance activities to ensure system availability [9]. Preventive maintenance is triggered by fixed intervals. If the end of an interval for a component is reached the item is overhauled or replaced. Whereas, corrective maintenance means that an item is fixed if an error occurs or if an inspection indicates a timely failure [3] [4, 6, 8].

Given the assumption that a failure of an item causes always a significant waste of resources and should, therefore, be avoided, a predictive maintenance program has to be set up by the management. But it is also to be noted that preventive and corrective strategy is very cost intensive. Concerning preventive maintenance work is performed on faultless items and the system must be disturbed before a maintenance task is initiated. The corrective strategy leads to long downtimes due to insufficient scheduling [3] [4, 6, 8]. Smart production is associated with the networking of components. If appropriate data of system states are collected and analyzed within a network there will be a basis for understanding the emergence of abnormalities. Decisive is, however, that the prediction of system states leads to a scheduling of maintenance tasks which ensures a very low downtime of the system. The future success factor of maintenance is therefore not the development and the implementation of maintenance workflows. Rather, it is far more necessary to have the competence to build up a suitable and meaningful analysis environment for predicting future system states.

2.5 Key area "Organization"

Maintenance departments in companies are in particular responsible for developing and implementing maintenance strategies for all of the equipment. But, planners who have developed such schedules for maintenance purposes are not often on the shop floor. As a result, the true states of the equipment, the failure modes, and effects as well as the consequences of the assets are not entirely known. Therefore, such plans are of little use. Another weakness is that the maintenance workforce on the shop floor evaluates these schedules as inefficient and as unwelcome paperwork [1]. Just as with all other reorganization processes it is of high importance to involve shop floor people and in particular the maintenance workforce in a formulation process for maintenance strategy. This can get individually adapted to the characteristics of the transition process towards a Smart Production.

Furthermore, the relationship and the cooperation between maintenance and production department has to be reorganized [1]. While in the past maintenance has been a cost-intensive support for the production in future times both departments must have common objectives regarding costs, productivity, quality, etc. A strategy for production and maintenance has to be developed interactively in order to ensure a close cooperation. Another option is the reorganization of the maintenance department to a profit center [8]. Also, in this case, common goals can be defined in order to achieve maximum efficiency for the whole company. Nevertheless companies today must focus its policies on promoting a work organization and workflows to make clear, maintenance is all about guaranteeing the functions and the performance of the work systems required by the users.

2.6 Key area “Personnel”

In current companies maintenance personnel is very important for precise working machines and equipment ensuring a high production quality and efficiency. Maintenance staff is normally well educated and qualified regarding mechanical, electrical and programming items. In their memories, deep knowledge regarding functions and properties of machines and components is accumulated. Particularly their cognitive and investigative skills are very valuable referring to fault analysis, troubleshooting and problem-solving.

Within the next decade due to the megatrend Industry 4.0 and regarding demographic changes the personnel situation in maintenance has to be adapted to new requirements and trends. Especially reduced availability of well-skilled experts on the market leads to staffing shortage in the companies. In parallel the need for maintenance staff in industrial enterprises increases. Reason for that is a higher degree of automatization and an increased complexity of machines and equipment. In this context, the demands on technical skills of maintenance experts will rise. Therefore, it will be a challenge for the next twenty years to manage employee qualification and knowledge-transfer within maintenance departments. To cover the personnel gap it will be necessary to transfer knowledge to assistance systems. Additionally, sensors, measurement systems and algorithm have to fulfill cognitive and investigative expert skills.

3 MAINTENANCE CHECK

Companies often stumble to identify their current status of the maintenance. Therefore, it is hard for them to develop a sufficient maintenance strategy. To enable the management to investigate their current maintenance status a maintenance check has been developed. Based on the identified key areas and the influence of Industry 4.0 ten main topics are defined in order to evaluate the maintenance status (see Figure 3).

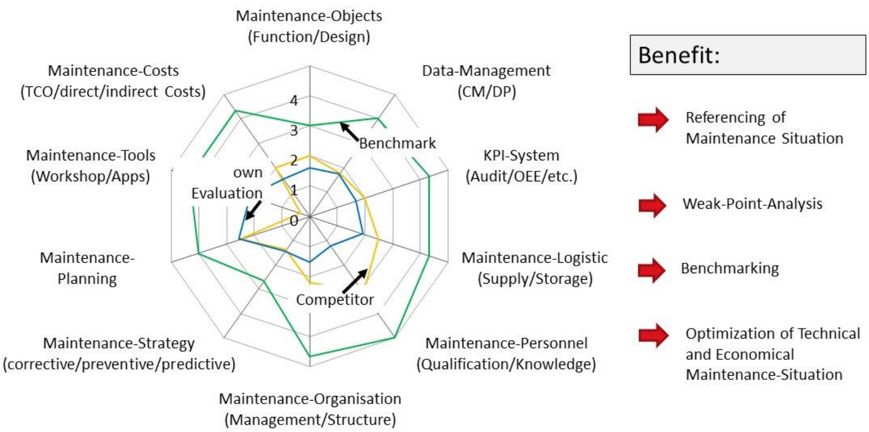

Figure 3: Structure and result of a maintenance check.

Each of the main topics contains more than ten questions for a detailed investigation and a description of the specifics of the company individual maintenance. For the identification of the range of each question and topic, different levels of a Capability-Maturity-Model are used. The levels have the description:

1. Initial;
2. Repeatable;
3. Defined;
4. Managed;
5. Optimizing.

Evaluations within the phase “*Initial*” often indicate that in the majority of the companies are still at the beginning with regard to maintenance performance. For example, some maintenance instructions are available but without any structure and a definition regarding the maintenance organization. The phase “*Repeatable*” describes that goals have been defined by the management

and first steps are introduced. In this case, maintenance objectives and an initial draft of a maintenance structure are defined. The next phase "*Defined*" leads to a comment regarding the maintenance structure of the considered company and results in a maintenance standard. The phase "*Managed*" shows that the maintenance standard is introduced and works along the processes of the company. Additionally, evaluations are carried out continuously in order to keep and to improve the maintenance level. The phase "*Optimizing*" stands for integrated maintenance management including a continuous improvement process. That means a standardized and robust maintenance process is established and improves itself.
The maintenance check can be carried out by the company itself or an external auditor. After an assessment, the determined values are inserted in a spider-web-diagram to get a representative overview of the results of the maintenance check. Additionally, the documented results are compared with the maintenance-performance of the competitors and the evaluation-benchmark. Finally, all ratings investigated for the different evaluation fields are added together, resulting in a total sum representative for the degree of maturity of each field. Thereby the need for action can be identified and suitable measures can be defined.

A further step of research work will be the development of a matrix which contains methods and measures linked to different maintenance objectives. For filling that matrix existing methods can be used but furthermore, new strategies have to be developed and established. Thereby, a structured tool will be available, which gives the opportunity to the service department to improve the maintenance situation in a systematic way.

4 CONCLUSION

Within the presented paper the paradigm shift in the field of maintenance of Moubray is introduced and discussed [1]. Based on the findings of Moubray six key areas are defined able to describe changes in the different fields of maintenance under consideration of a further digitalization of production processes. New paradigm considers all phases of a system, from procurement, operation through to the recycling of the machine. Evaluation of the current maintenance situation of a company can be carried out by a newly developed maintenance check. Evaluation of the maintenance status is operated by utilization of different levels of the Capability-Maturity-Model. The result of the evaluation is documented in a spider-web-diagram in order to give a review regarding the full maintenance situation. Future research work will deal with the development of a matrix containing methods linked to the different key areas of maintenance.

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ASSESSMENT OF LAYOUT SOLUTIONS FOR RESTRUCTURING A MANUFACTURING PROCESS

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Abstract
Planning the layout of machining and assembling departments is a common problem for mechanical industries that aim at improving their production performance. Indeed, the relation between complicated layouts and poor productivity has been confirmed by several studies. In this respect, two key decisions are the precise positioning of machines and the planning of buffer capacity. Several approaches to layout analysis have been proposed: some employ optimization techniques taking into consideration traditional performance measures, while others are based on more recent management concepts, such as lean manufacturing or quick response manufacturing, and use heuristic methods or simulation.
The paper presents a study carried out in a manufacturing company which produces ship engines, focused on two departments: component machining and module assembly. The study examined a project for material flow improvement based on lean manufacturing concepts and tools. In particular, the Value Stream Mapping was employed, which allows analyzing the “as-is” and outlining the “to-be” situations, eventually leading to the redefinition of the production layout. In accordance with the waste minimization principle, it was decided to realize a new warehouse with a capacity lower than the pre-existing one. Such decisions, however, required to minimize the congestion of the internal routes, in order to supply the needed material at the right time with an adequate fleet of forklift trucks.
To validate the effectiveness of the foreseeable results and understand the behavior of the entire production line, varying some parameters and the new truck fleet in place, a simulation model was carried out, which allowed to establish the operational feasibility of the proposed solution.

Keywords:
Layout, Material flow, Lean manufacturing, Simulation, Logistics

1 INTRODUCTION

The ever-growing competition in the manufacturing sector exerts pressure on companies to take measures for improving their production processes. In job-shop or assembly systems, when it is not viable to introduce technology changes in plants or machinery, improvements to the process layout may be carried out in order to reduce problems concerning low production efficiency may reside. In fact, it is well-known that layout influences productivity and the efficiency of equipment use [1, 2]. Some authors [3, 4] have studied layout optimization by implementing the principles of lean management, applying simple algorithms or a mix of lean tools, which entail significant improvements in productivity in various work areas; others [5, 6] proposed to embody the principles of lean in optimization or simulation. Several studies show that the improvement of the production process can be obtained by the reconfiguration of the existing layout with the precise positioning of the machines, the correct sizing of the buffers necessary for the production flow and the optimization of the transport paths used for feeding the production lines. The study here presented employs lean management tools to reorganize the layout of a manufacturing plant. In order to understand the behavior of the entire production line and to assess the effectiveness of the solutions, a simulation model was built in which the findings of the application of lean manufacturing principles were tested.

2 ANALYSIS OF THE PRODUCTION PLANT AND PROPOSALS FOR IMPROVEMENT

The analyzed plant in which naval propulsion modules are assembled consists of two buildings. In the first, the smaller parts of the engine (cylinder heads, connecting rods, etc.) are prepared and processed. In the second building the engine is assembled; this operation is subdivided into two processes:

- Machine work on the engine block with different processing steps that can take a long time (a few weeks).
- Assembly of the motor in two phases: heavy preassembly (subdivided into five stations where the engine stops for two days and during the night it is moved to the next station) and main assembly in a 14-station cell, where some tests are performed before delivering the engine to the testing room.

The project investigates the opportunity to move some of the above-mentioned activities into a single building in which a new warehouse, with a capacity lower than the existing one, should also be located. In the new building, internal supply routes must not be congested and the number of forklift trucks should be sufficient to guarantee the supply. In order to define the future layout of this building, it was decided to apply the Value Stream Mapping (VSM) methodology, which helps to analyze the current value stream, detect waste and define the future value stream in which waste is eliminated [7, 8, 9]. The pre-assembly section of the connecting rods for different engines was analyzed. Connecting rods were divided into two parts, the connecting rod shank (stem) and the connecting rod end (head), because they are part of two different production lines. The raw product can be manufactured by the internal FMS work-center or externally supplied. To obtain the finished product, the connecting rod shaft requires a series of operations, which were subjected to work sampling. From time measurements it was possible to elaborate the Current State Map (Figure 1). Both the internal FMS and external suppliers can supply the connecting rods and this allows the plant to perform the internal activity continuously, even in presence of a fluctuating demand. A careful analysis of the current situation enabled the identification of waste, the possible improvements and, therefore, the future state map that is shown in Figure 2.

The analysis of the single operations and their changes are not discussed here. However, the improvement of the production process in terms of waste elimination is summarized in Table 1. The reduction of time by removing non-value-adding activities allows achieving a more continuous flow and a drastic decrease in buffer size. The same procedure was then carried out for the connecting rod shaft and the improvement of the production process in terms of waste elimination is reported in Table 2. Unlike the connecting rod heads, there is no increase in the ratio between the value-added time and lead time (value-added efficiency): this is due to the equal proportional reduction of the value-adding and the non-value-adding time in the future state situation.

Table 1: Features of the production process of the heads of connecting rods.

Connecting rod heads	*Current (h)*	*Future (h)*	*Variation in hours*	*Percentage variation*
Value-added time	2.2	2.4	0.2	10 %
No value-added time	109.7	24.8	-84.8	-77 %
Lead time	111.9	27.2	-94.6	-76 %
Value-added/Lead time	2 %	9 %	N/A	7 %

Table 2: Features of the production process of the stems of connecting rods.

Connecting rod stems	*Current (h)*	*Future (h)*	*Variation in hours*	*Percentage variation*
Value-added time	5.2	3.1	-2.1	-40 %
No value-added time	70.7	43.1	-27.6	-39 %
Lead time	75.9	46.2	-29.7	-39 %
Value-added/Lead time	7 %	7 %	N/A	0 %

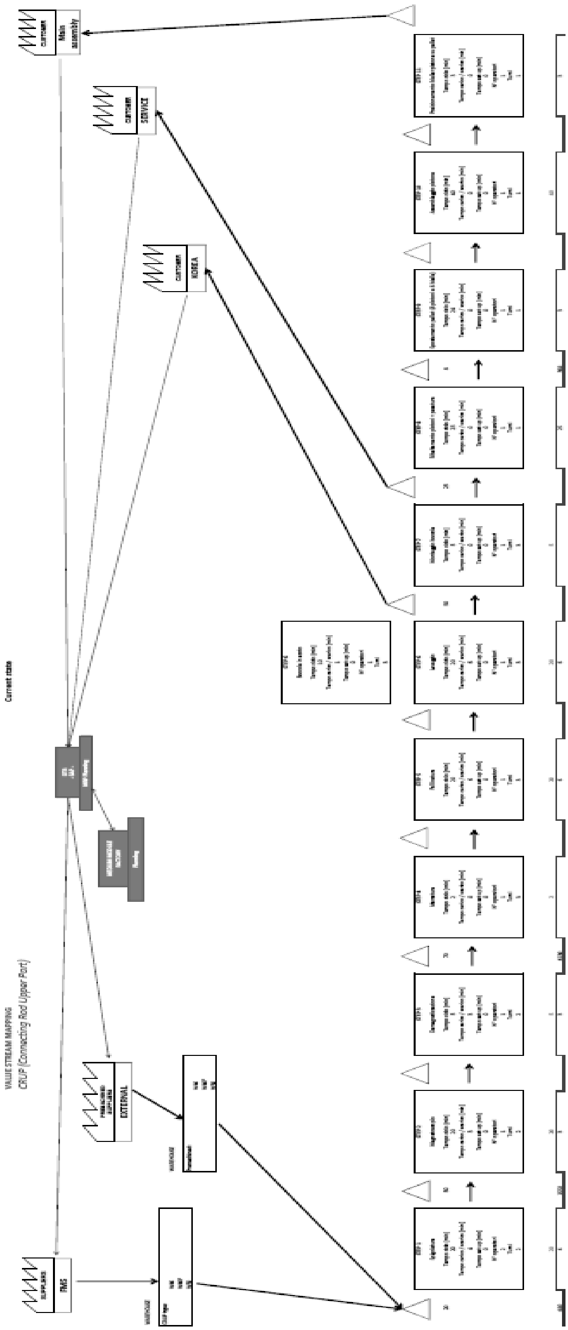

Figure 1: Current state map.

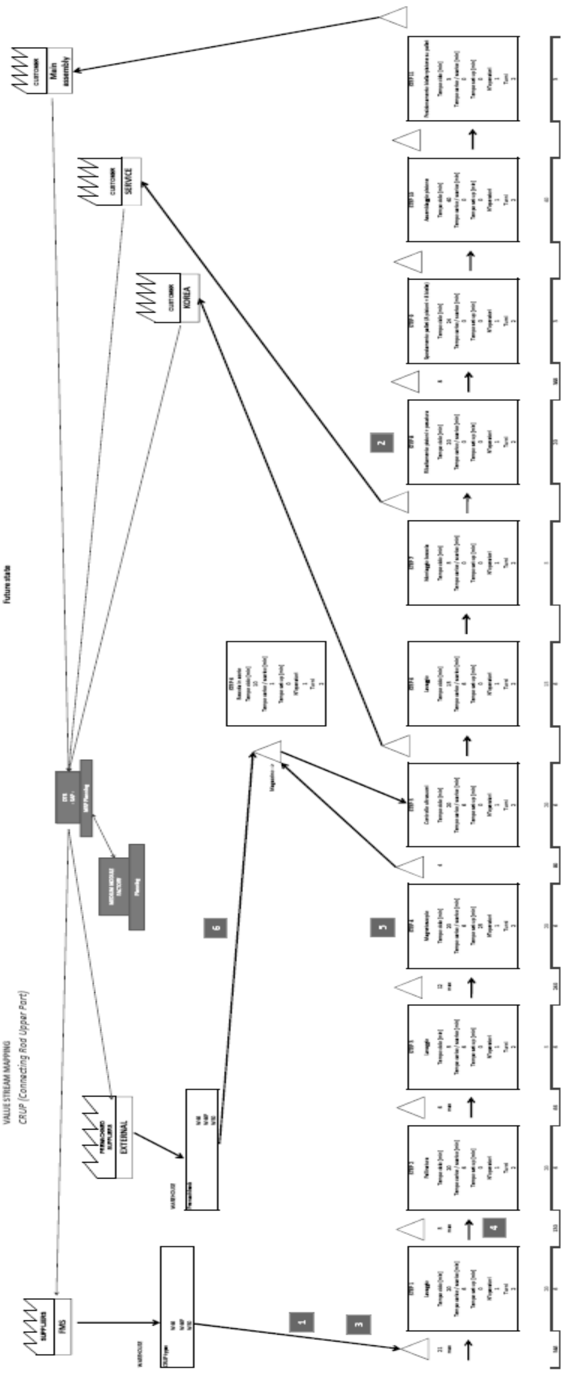

Figure 2: Future state map.

The space available for the production line relative to the connecting rods and the assembly of the pistons was 1500 m^2 and the goal that guided the definition of the layout was the continuity, the homogeneity and the linearity of the production flow, compatible with the production constraints. Various scenarios have been developed and the spaghetti chart methodology has been applied to reduce the paths between workstations and to improve the fluidity of the route. The changes made, in addition to making the flow more linear and homogeneous, led to a drastic reduction in movements (Table 3).

Table 3: Comparison of route length in current and future layout.

Route length (m)	*Current layout*	*Future layout*	*Variation*
Heads of connecting rods	218	121	-44.5 %
Stems of connecting rods	256	172	-32.8 %

The areas of current and future configurations are very similar. In fact, the available area (total space for arranging machinery, warehouses, passages, etc.) is about 1500 m^2, while the net area occupied by machinery is about 1000 m^2 for both scenarios. In the future layout, there are some dedicated warehouses where both the externally supplied components, ready for ultrasound testing, and the internally supplied components will be stored.
Following the modification of the layout, which produced a space reduction higher than 50%, the effects of unifying the two existing warehouses with the future were analyzed. This part of the study aimed at verifying whether the production is supplied on time and constantly, if the routes are not congested and if the number of forklifts is sufficient. To do this, a data collection was carried out to map the factory, which included the analysis of the production plan, the identification of the number of pallets needed for production and the definition of the times for assembling the engine, taking into account the delivery time of the material.

3 SIMULATION OF THE FUTURE PRODUCTION PROCESS

3.1 The simulation model and the first experiments

A simulation model was built to understand the behavior of the entire production line as the parameters and supply system vary and validate the effectiveness of the technically feasible results. The model is always a simplification of the actual system; however, simulating a new system is sometimes the only possibility to study it as the actual plant cannot be observed [10]. The simplified hypotheses adopted in the case study are:

- Overhead cranes are not modeled.
- Cycle time is the sum of machine time and operator time.

The graphic representation of the model using the Witness® object-oriented software is shown in Figure 3. Two flows can be noted: the upper one is relative to the heads while the lower one is relative to the stems of the same connecting rod. The two flows join at the magnetoscope station, where the operation is performed on both components. The incoming pieces are provided by the FMS with a regular time (it works 24 hours a day) except for Saturday and Sunday. A buffer is placed between each machine (output from the previous one and input to the next one). The 12 buffers act as decoupling buffers between one machine and the next. Once the last operation is completed, the parts are released from the flow. The heads of the connecting rods, which are daily supplied by the FMS, are 16 halves for a total of 8 pallets (2 half-heads per pallet) with an inter-arrival time of 360 minutes. The stems of the connecting rods are 8 for a total of 3 pallets (max 3 stems per pallet) with an arrival time of 540 minutes.
Almost all the workstations are run by a dedicated operator; only in the case of the washing machine and shot-peening machine, the activities are run by a single operator.
The cycle times emerged from the VSM were considered and for the input and output commands to the machines, it was established that they are free and that the relative set-up is carried out. The 8-hour work shift (480 minutes) in the morning and afternoon is paired with two breaks of 15 and 45 minutes, while in the night shift there are four breaks of 15 minutes.
As samplings cannot be collected in the future system, a validity check of the model was performed by comparing the planned values of some parameters with those obtained from the model execution. Particularly interesting was the average flow time of parts in the process. The flow time of the connecting rods obtained from the simulation differs for only 0.7% with respect to the calculated theoretical one; this is possibly due to the simplification adopted at the station where the washing machine and the shot-peening, where only one operator is available.
After the validity check, the experimentation phase was performed. First of all, an analysis was carried out to find the saturation of the system obtained by not placing constraints on the number of incoming pieces, i. e. limiting the capacity of the buffers. A two-month warm-up time was introduced and after that, a one-year production period was considered. An initial production of 7 pieces/day (7 stems of connecting rod and 14 half heads of connecting rods) was taken into consideration, with 2 shifts and 5 working days per week and then increasing the pieces produced daily to saturate the line. Not having set limits to the buffers, it was decided to increase the shifts only if the buffer quantity tended to infinity during the simulation. The shifts have been set for each individual machine in order to have maximum flexibility: from 2 shifts a day for 5 working days a week, we have moved to 3 shifts for the same period and then for 7 working days a week.

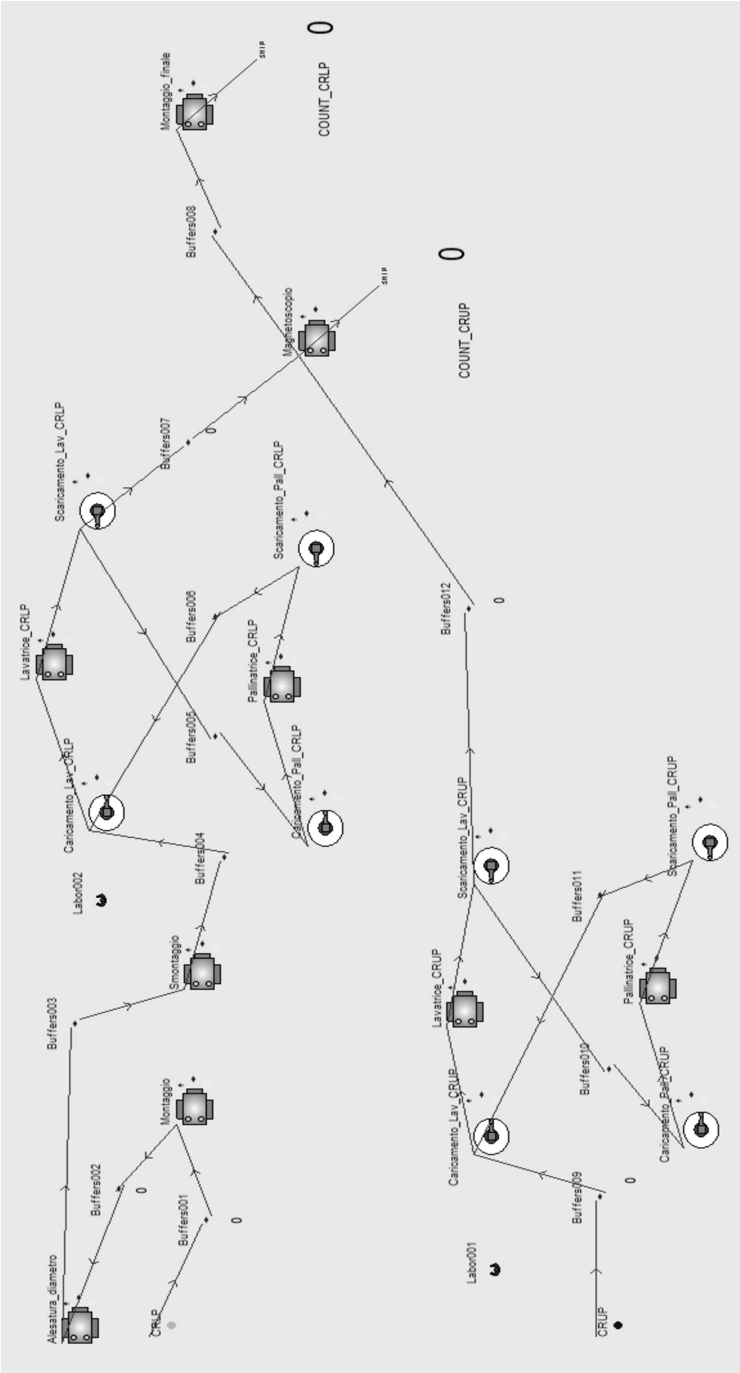

Figure 3: Simulation model of the future configuration.

The maximum number of pieces theoretically feasible per day is 18 because the magnetoscope is the bottleneck of the system even operating with 3 shifts for 7 working days per week. This analysis is theoretical in that the capacity of the FMS is lower than the capacity of the process in which the stems and the heads of connecting rods are manufactured. From the simulations, it is found that the two lines of the stems and heads of connecting rods are well balanced and produce in a year almost the same number of pieces.
The first simulation experiments considered 4 cases:

- 2 cases with the above-mentioned hypotheses.
- 2 cases with the peculiarity of having limited buffers and submitting machines to preventive maintenance (at regular intervals, 2 hours every 2 months for each machine) or corrective maintenance (described by triangular probability distributions).

The situations related to 8 and 12 pieces/day were considered, with a "target" production for the FMS. A 2-month warm-up time and a 1-year analysis time has been adopted. Also, in this case, the number of produced pieces is practically the same for the line of the stems and the heads of connecting rods. There is a perfect correspondence between the numbers of pieces produced in the 4 cases, this means that the maximum buffer limitation and the introduction of maintenance did not bring changes in the flow of the system since the machines are not saturated. The buffer size in the ideal cases could have been greater than that of real and limit cases; the fact that this does not happen proves that the production lines are well balanced. Finally, the percentage of occupation of the machines was calculated, which shows the perfect concordance between the ideal and the real cases, which demonstrates the correct choice of the space reserved for the buffers in the definition phase of the layout.

3.2 Second experimental phase

Having available the product plan, the number of pallets for each engine and the times for assembling the engine and taking into account the delivery of the material, a new simulation model was created. The adopted simplifying assumptions neglect some minor internal logistic activities (preparation of pallets and kits), production movements, out-of-shape and overweight pieces, and engine lifts that prevent passage of forklift trucks. The initial conditions are: single starting point corresponding to the center of the new warehouse area, a pallet corresponding to a trip, return journey which can be different from the forward one, all the pallets are ready in the morning, line operational use of the different engines, sequential choice of the station, merging of engines into families, maximum capacity of pallets in the warehouse, capacity of the tracks, and shifts and the plant closure days in a year. The data related to forklifts are: speed 6 km/h, 1 minute of waiting before leaving the warehouse, 1 minute for loading, 1 minute for unloading, 2 minutes of parking after its arrival in the warehouse, the capacity of forklift trucks (1 pallet) and a variable number of forklift trucks (3 fixed and 3 backup forklifts). The results to be achieved are: there are no pallets left in the warehouse at the end of the day, maximum delivery delay of pallets of 1 day, and leveled daily workload. The variables involved are the number of operators and the daily time slots that the logistic function dedicates to the delivery of the material. Since the available space cannot change, the internal routes are the same as in the current situation (Figure 4). The red dots in the figure represent the points of arrival and departure of the pallets from and to the warehouses. Some paths will be used by internal production, others for goods acceptance and storage, and others for handling the finished products.

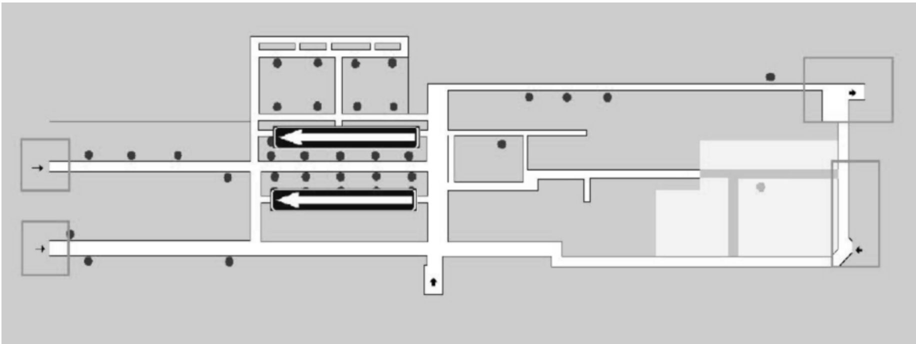

Figure 4: Initial situation of one-way routes and unloading areas.

The validation of the model was made taking into account the total annual hours spent by the forklifts transporting material. Considering a 70 % efficiency of the forklift driver, the difference between the real situation and the simulated one is 5 % (127 working hours), which shows a good reliability of the model, despite the introduced simplifications. The model was used to evaluate the improvements that will be obtained with the new layout at the same workload level. Five scenarios were tested that considered the following goals:

- The congestion of routes must be less than 50 %.
- Production must be supplied in the right time and without delays.
- The number of forklifts should be minimized without negatively affecting the previous goals.

Scenario 1: travel directions

In the initial configuration, the saturation percentage of the route to and from the warehouse was higher than 65 % and, in some cases, it was blocked (unacceptable situation). After deciding to make it a one-way route, almost 91 % of pallets deliveries were on time, while only 9 % late. Going however to analyze The average days spent by a pallet in the warehouse (days of supply) were 0.53 days and the standard deviation 0.35 days; such results show that the delay is minimal (only 0.29 % of the pallets has a delay longer than two days). Since the pallets that are not shipped on Friday can be delivered on the following Monday, this value can be neglected. As for the use of forklifts, three are always available within the time slots dedicated to production supply, while the other three come into play when the warehouse load increases. In the future situation, it will be sufficient that three forklifts are always available and two as a backup when the workload is higher.

Scenario 2: same as scenario 1, but forklift speed is reduced to 4.5 km/h
The simulation experiments show that the routes are not congested. The days of supply is 0.66 days (average) and the standard deviation of 0.48 days. The delayed pallets are 14 %, which is 4 % above the threshold limit. A solution is to improve the workload balance in order to improve the usage of forklifts within time slots. Forklift use varies greatly (they are slower) and the pallets are evaded from the warehouse with a lower frequency, while backup forklifts are more used. The distance traveled per year is the same and the number of hours of use is 4,130 h with an improvement of 0.65 %.

Scenario 3: same as scenario 1, but forklift speed is increased to 8 km/h
Also in this situation, the routes are not congested. The days of supply is 0.46 days (average) and the standard deviation of 0.29 days. The delayed pallets are 7.5 %, which is within the parameters' limits established initially. Forklift use varies greatly (they are faster) and pallets are evaded from the warehouse with a higher frequency, while backup forklifts are less used. Balancing the workload, it would be possible to use only 3 forklifts to manage the annual deliveries. The distance traveled per year is the same and the number of hours of use is 4,130 h with an improvement of 39.0 %.

Scenario 4: same as scenario 1, but with the difference that once every three weeks the warehouse does not process any pallet, thus increasing the workload on the next day. This scenario simulates different real situations: production delays, breakage of one or more forklifts, possible errors in logistics or suppliers and blockage of the warehouse. The experiments show that the routes are not congested. The days of supply is 0.52 days (average) and the standard deviation of 0.79 days. The delayed pallets are 17.5 %, which is 7.5 % higher than the threshold limit. This means that attention must be paid to the production plan and suppliers' dependability, and a quick maintenance service must be activated to ensure the availability of the forklifts and warehouse. The use of forklift varies a lot (variable workload with peaks due to blockage of the warehouse) because the unbalanced load implies periods of great use, especially of backup forklifts, and periods of inactivity. The distance traveled per year is the same and the number of hours of use is 4,130 h with an improvement of 8.0 %.

Scenario 5: same as scenario 1, but with production at maximum capacity (35,500 pallets to be delivered per year).

Also in this situation, the routes are not congested. The days of supply is 0.83 days (average) and the standard deviation of 0.82 days. The delayed pallets are 17.5 %, which is 7.5 % higher than the threshold limit: the considerations of scenario 4 are therefore valid in this case too. The use of forklifts is intensive and the number will be at most 5, of which 3 are always available and two are used as backup. The distance traveled per year is the same and the number of hours of use is 4,130 h with an improvement of 48.2 %.

4 CONCLUSION

The purpose of the work was to define the new layout of an industrial plant in order to improve the production process of a mechanical company. To make this restructuring, it was decided to initially apply Value Stream Mapping, defining the "as-is" situation and outlining the "to-be" situation. To test the results obtained, a simulation model was created to verify the saturation conditions of the machines, the maximum size of the inter-operational buffers and the balancing of the production line. Furthermore, in order to avoid congestion of the routes (50 % lower) and ensure production dependability (delay must not exceed 1 day for 90 % of pallets and less use of forklift), different scenarios were investigated which entail a total improvement of 48.2 % in maximum capacity and a reduction of the number of forklift trucks to 5 (3 always available and 2 as backup). The proposed methodology, which could be applied to any manufacturing company for the redevelopment of the plant layout, proved to be effective in testing lean manufacturing practices in a simulated system without the need to stop the production process or carry out pilot projects on limited portions of the actual system.

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ROBUST PLANNING OF THE PROVISION OF COMPLEX SERVICES

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Abstract
A high level of productivity for current and future services is a critical success factor for companies. When the productivity of services is unknown or incorrect, resources are wasted and opportunities are missed. To respond to this challenge, a simulation model for the prospective description of a complex service provision was developed in order to support companies to create a robust offering of services. Focusing on the domain of factory planning, we illustrate how an extended Stochastic Resource-Constrained Project Scheduling Problem (*SRCPSP*) can be applied for developing proposals. The presented validation study confirms that the approach is capable to calculate and optimize the planning objectives when developing a service for complex engineering projects.

Keywords:
SRCPSP, Simulation, Petri Nets, Proposal development

1 INTRODUCTION

The service sector is no less depending on well-calculated proposals than the manufacturing sector but in a rather different way. But the recent surge in research activities attempts to define the differences between creating values for the customer. Hence the process of planning and calculating costs of a service provision is almost ignored.
How strong are service companies in terms of developing correct and robust proposals? Until the last five years, this question was hardly raised at all. Complex engineering projects, such as factory design and architecture services are particularly prone to disruption or failure. Expressive examples are the Airport Berlin or the Elbphilharmonie in Hamburg. In both projects, the high levels of time and resource dependencies make such a complex service provision susceptible to unforeseen events and delays. The cost calculation and the schedule of the initial proposal are from the present point of view highly incorrect. Therefore, it must be concluded, developing and calculating proposals for complex service projects are a challenging task. The dependencies between tasks have to be considered for a specific service scenario and decisions must be often made within a short time. To this day

managers of services develop proposals based on the current situation of the company and according to their individual experience. With regard to scheduling and calculating, simulation models can be used to generate and analyze heterogeneous scenarios which can occur during service provision.
Our work was motivated by the insights and findings of a study conducted with several large architecture offices in Germany. Based on the requirements of these companies we primarily realize a simulation model for developing proposals for different service scenarios.
The paper is structured as follows. In Section 2 the management of proposals for complex services is defined. Subsequently, we describe the simulation framework of our model in Section 3. A use case is presented to provide a statement regarding the expected benefit of a simulation-based development and evaluation of proposals in Section 4. Section 5 summarizes the contributions of this paper.

2 PROPOSAL DEVELOPMENT

A service system is defined as an arrangement of resources including people, organizations, shared information, and technology. The links between these entities are internal and external and are set up to generate value propositions [1]. With the increasing complexity of service provision due to the number of tasks and resources involved, knowledge-intensive services are often considered as a project. Therefore, Lusch et al. [2] define service provision as combinations of actors interacting to co-produce service offerings, exchange them, and co-create value. This interaction should be planned in advance to allow for the best possible productivity.
A proposal for such a complex service contains information regarding the conditions under which the service provider would accept to provide the service for a customer. Content of a proposal may be the objective of the service, nature and content of the service, the period of the provision with milestones, costs, involved employees, and method of payment etc. Such proposals for complex services are associated with risk due to the uncertainties pertaining to information on the availability of employees and the prospective evaluation of the effectiveness and efficiency of task processing. In practice, manifold unforeseen events often make a deviation from the planned service provision necessary. But, it is often difficult, to dynamically adapt a proposal which was accepted by the customer due to a changed situation or an incorrect planning.
Therefore, we think that service companies need a consolidated proposal management. What we mean by proposal management is the process of creating and selecting an appropriate set of information to prospectively describe probable service scenarios and to derive the service goals to be achieved. The prime objective of proposal management is to define and describe the cost, duration and the content of a service. However, in order to optimize the economic efficiency, the optimal relation between guaranteed

service and price has to be identified. A proposal management problem can be defined as a resource-constrained scheduling problem. This consists of 1) a service product to be produced, 2) a work schedule for the service provision, 3) limited resources, and 4) the objectives for the service provision. It is solved through the process of proposal management. The starting point for developing a proposal for a service is the cost estimation. Cost estimation modeling techniques can be fundamentally divided into parametric models based on statistic, individual knowledge of the managers, or machine learning [3].

The HOAI - German Fee Regulations for Object Planners and Engineers is an example of the analytical development of a proposal for factory planning projects. Thereby, defined phases provide detailed and clear information about the service at each stage. Based on the specifications of the HOAI the computation of fees is based on the construction costs that are determined based on the design development. Since the European Commission has instructed the national competition authorities to proceed against the directives on fees of associations and special-interest groups new approaches for calculating service proposals are necessary [4].

To conclude, to the best of our knowledge there is currently no approach available for a proposal development which is based on a prospective description and evaluation of the likely courses of a service provision.

3 SIMULATION FRAMEWORK AND SIMULATION MODEL

3.1 Workflow modeling with Petri Nets

The provision of a service is hard to be predicted in advance. For a prospective description of the individual states of a service, the Petri Net method is used. A Petri Net is a graphical and mathematical modeling method which can be used for a visualization of a system status. The primary difference between Petri Nets and other modeling methods is the presence of tokens which are used to simulate concurrent and asynchronous status changes in a system. The dynamic based on status changes can be represented in a Petri Net by setting up state equations, algebraic equations and similar mathematical models [9]. A Petri Net is a directed bipartite graph with nodes and arcs (Fig. 1). The nodes represent places and transitions that can be activated accordingly to the system status. A directed arc connects one place with one transition. A direct connection between places or transitions is not allowed. Places in a Petri Net may contain a discrete number of marks (tokens). A transition of a Petri Net fires, whenever there are sufficient tokens in the input places and, if applicable, other conditions are met. However, the latter may be the minimum holding period of a token in the input place. When a transition fires, a predefined quantity of tokens are consumed and tokens in the output places are generated. Thereby, a firing of a transition cannot be interrupted.

Heterogeneous variants of Petri Nets are introduced in the modeling literature: untimed; timed; colored; stochastic; predicate; priority etc. [9]. These are successfully used in the areas of business process modeling and service management [10, 11]. For a further introduction to graphical modeling of processes using Petri Nets, the reader is referred to van der Aalst and Stahl [10].

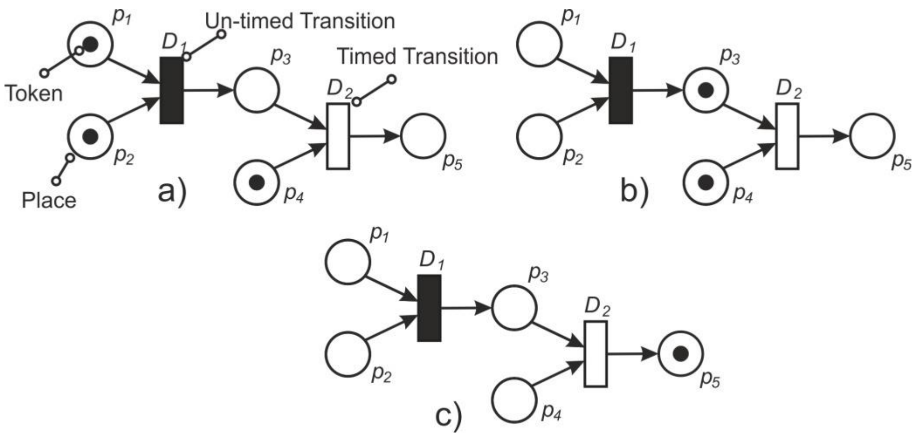

Figure 1: Single states of a Petri Net: a) initial marking, b) marking after firing of D_1 c) marking after firing of D_2.

3.2 Simulation framework

The simulation-based development of a proposal requires an adequate level of information as an input to the model. Through the use of transformation guidelines, a graphical process model such as Business Process Model Notation is transformed into a simulation capable time-extended higher level Petri Net.

The implementation of our Petri Net based simulation model was carried out with the programming language Scala. With our implemented concept users are able to configure and parameterize pre-defined, standard sub-models of Petri Nets which describe tasks and work packages of the considered service. Afterward, the individual sub-models of tasks are combined with the help of logical operators. These operators cover AND, OR, XOR-decisions as well as an iterative execution of one or several tasks. The core element of our concept is the sub-model task processing (Fig. 2).

This model consists of four transitions (D_1, D_2, A_i, T_1) and five places (p_1, p_2, p_3, p_4, p_5). The arcs link the places and transitions of the model. The place p_1 serves as an interface with all predecessors j of task i or the logical operators. If all the predecessors are sufficiently processed, the initial state occurs and a token is placed in p_1. The transition D_1 is activated and triggers the decrement of a timer value. The initial timer value is specified by the decision variable v_{ij} and determines when the transition D_1 fires. The adaptable timer value defines the time period between the initial processing of a task and the completion of all of its predecessors. This timer can be also used to define an overlapped processing of tasks with a common precedence relation. The token of p_1 is consumed and a new token is set in p_2. The latter represents the assignment of a task to at least one employee. This function can also be used to check the availability of restricted tools and information. A token in place p_2 indicates that the conditions of processing this task are created and the expected execution time can be calculated.

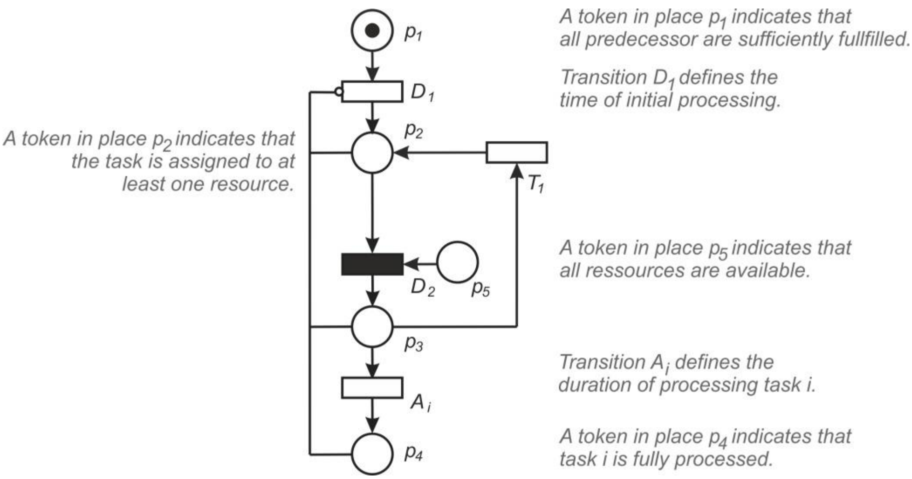

Figure 2: Sub-Model of a task.

If all employees assigned to a task are available and they all intend to process this task at this stage, a token is set to place p_5. This process is controlled by a specific programmed Scala function. The availability of all employees assigned leads to a consumption of the token in p_2 and p_5 and a direct firing of D_2. The token set in place p_3 causes an activation of the transition A_i. The timer for the activation of A_i is set to the value of the calculated duration of task processing. The specification of the value may be fully deterministic, although a stochastic proportion can be optionally declared by the user. The activation of A_i remains until the timer value is reduced until zero (full processing of the task) or the token in s_3 is consumed due to a firing of T_1. However, the latter represents an interruption of a task processing due to a non-working period of the assigned employees or a modified prioritization of tasks to be executed. If the timer of A_i is zero, A_i fires and a new token is set

in p_4. Due to the backward oriented arcs $L(p_2,D_1)$, $L(p_3,D_1)$ as well as $L(p_4,D_1)$ a new activation of D_1 is disabled.
A firing of at least one transition causes an individual change of the state of a Petri Net which represents an instance of the incremental processing of the service. Thereby, constraints limit the firing of transitions.

4 USE CASE

In this section, we discuss the results of a use case that indicates that the proposed simulation model provides us with a good description of the objective space. We describe the experimental setup and the scheduling task before summarizing the obtained results. Note that the intention of this evaluation is to show the general applicability of our simulation model rather than to evaluate the speed of execution. Thus, the problem representation, the simulation model and the corresponding evaluation results should be considered as a starting point for a simulation-based development of proposals for complex services.

4.1 Scheduling problem

The scheduling problem is derived from a service process for factory planning. At the time the management of the architectural office had the task to make an offer for the design and construction of an industrial building. The whole factory planning project comprises 80 work packages during the HOAI phases No. 1 to 9 (concept, execution planning, tendering and construction management).
In the derived case study, two conflicting objective functions are considered: duration and costs of the service. Because not all durations or rather each amount of work for the work packages were known in advance, the designed simulation model consists of deterministic or stochastic durations subject to precedence- and resource constraints. If the durations of a model are stochastic, optimality of the solution cannot be guaranteed. Therefore we have to point out that the solutions of such a *SRCPSP* are a policy rather than a schedule [5]. Based on the concept of the Program Evaluation and Review Technique (PERT) the so-called three-point estimation (optimistic (a), most likely (m), and pessimistic (b) duration) is used to describe the distribution of each work packages, and to define mean and variance values of the probability density function [6]. Due to probability distributions, a simulated duration and a calculated probability of occurrence for each work package, the analysis focus on the development of a distribution for the duration and costs of the entire service. For this purpose, we utilize the central limit theorem of probabilistic theory and causal link between duration and costs of a work package. We assume that with a rise in duration the costs increase proportionally. According to this, the total duration and cost will follow a normal distribution within the domain of practical interests.

4.2 Simulation model and simulation study

Our simulation model corresponds to a multi-skill scheduling problem with stochastic durations. First of all, the duration of each work package is calculated based on the related probability distribution. As a next step, the model determines the reduction of the duration due to the number of employees assigned as well as the skill levels of the scheduled employees. Thereby, it is assured that the skill requirements of a work package are met without violating the minimum and the maximum number of employees.

The structure of a service can be represented by a directed cyclic graph with precedence relations between work packages. Each of the work packages is non-preemptable, i.e., once started they have to be completed with no interruptions and no changes in the assigned employees. Furthermore, the model includes alternative routing of work packages as well as the potential occurrence of iterative processing.

Initially, 10,000 stochastic independent simulation runs were executed to generate the required information for a first draft of a proposal. According to this scenario, it is assumed that no modifications of the planning task will occur during service provision.

But, changes are a significant characteristic of factory planning projects, induced by the contracting authority. In reality, however, the contracting authority often modifies significant characteristics at a late stage of the service provision. We have interviewed experts from the field of factory planning and as a result, relevant scenarios concerning changes of customer requirements were defined. For each scenario, the experts determined the likely time of a modification and analyzed the effects, in terms of the characteristic of work packages and precedence constraints. The simulation model was adapted accordingly and 10,000 stochastic independent simulation runs were executed for each scenario. To provide a statement regarding the expected benefit of our model, we will consider a significant change during stage construction supervision (HOAI phase No. 8) in detail. Such an amendment has a significant influence on implementation planning (HOAI phase No. 5). For example, the contracting authority modifies the building structure and the spatial grid in an advanced stage of the project. In practice, this leads to a renewed processing of already completed work packages from phase No. 5 and an effort for unprocessed work packages that was not anticipated.

4.3 Results

To the best of our knowledge, no public benchmark data exist for a simulation model with alternative and iterative task execution. The only option would be to compare the following results with scheduling problems of *RCPSP* libraries to consider predecessor constraints and resource allocation [7]. Such a verification study for the developed simulation core is described in [8].

The following findings can be derived based on an analysis of the distributed solutions in the range of results [12]. The scatterplot in Fig. 3 highlights the areas which are more often identified by 10,000 simulation runs. If a vector

(duration, cost) is developed more than 6 times the objective values of the corresponding plans have a high probability of occurrence during a service provision. Each point within the objective space in Fig. 3 represents a plan for a valid service provision. Such a plan provides detailed information regarding the planned costs and the period of processing a work package, the assigned employees as well as the risk of implementing the plan. This information forms the basis for a detailed proposal of the intended service. In the case that the customer makes a concrete specification regarding the objectives, the service provider can use the scatter plot to evaluate the risk of a fulfillment of the given objectives and for further negotiations.
The comparison between the simulated object space and the proposal developed from the management shows that the latter should be evaluated as risky. Thus, the proposal of the management is based on eligible costs of 620 T€ and a total duration of 25.3 months. This combination of values has been identified only with a very low frequency by our simulation model. Therefore, we would suggest values which are in the center of the scatterplot. In our case, the combination of duration and costs with the highest probability are in the area 26.34 months (SD = 1.68 months) and 703.36 T€ (SD = 36.42 T€). If a significant change during the phase construction supervision is expected an iterative processing of tasks has to be considered in the model. Re-executed simulation runs yield a modified location of the scatterplot. As a result, the probable expenses increase (MW = 903.73 T€; SD = 54.12 T€) and the anticipated service provision may be delayed (MW = 29.85 months; SD = 2.03 months). The result of the simulation emphasizes the negative effects of making such late changes and maybe a qualified basis for the discussion with the contracting authority. However, the results of a simulation study can be used for a supplement cost calculation.

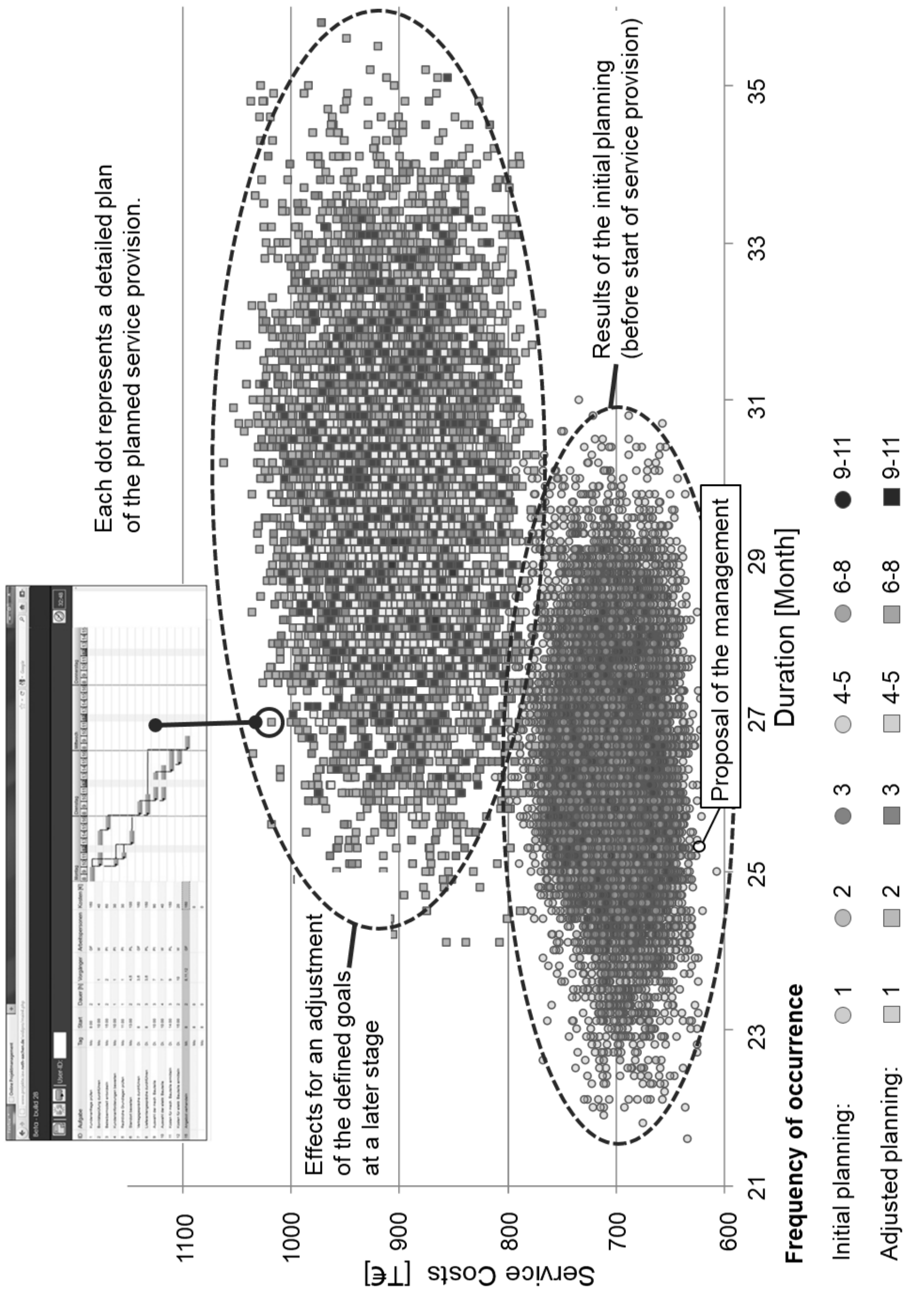

Figure 3: Scatterplot of the frequency of developed proposals.

5 SUMMARY AND CONCLUSION

This paper proposes a comprehensive approach for developing robust proposals for complex service provisions. Based on examples from the domain of factory planning, it was shown that a simulation model is suitable for many real-world proposal preparation processes. We figured out that it is necessary to consider alternative process execution paths in order to minimize financial risk for the service provider. Motivated by the lack of possibilities to develop and analyze different service scenarios with a minimum effort, we subsequently introduced our framework of a simulation model. This model facilitates the considerations of stochastic durations of tasks as well as variations in the process execution path. Therefore, a combination of planning and scheduling is achieved.
Besides the simulation model, we also provided several modeling patterns which can be used as a guideline when developing robust quotations for complex service provisions. The performance of the simulation model was analyzed in an experimental evaluation using a real-world planning problem of various size, resource complexity, tightness and so forth. Importantly, it became obvious that the simulation model develops the objective space for different service scenarios within one hour. Whilst the duration may be high, we are sure that our approach will support managers to improve the quality of proposals for complex services.
Recently, we are working on a concept to reduce the time required for parameterizing the simulation model for a specific planning problem. Finally, a set of test cases for developing proposals is provided in near future.

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LEARNING FACTORY AT FSRE – UNIVERSITY OF MOSTAR

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Abstract
In today's economy, the production sector is one of the most important pillars. Current challenges range from the increasing fragmentation of markets, individually customized products or inconsistent demand and sales. To cope with such challenges companies need to enable quick adaptations to changing market conditions. Employee's competencies are the key resources of an enterprise to quickly adapt to ever-changing conditions. One promising approach for the effective development of competencies is the learning factory (LF). In recent years more and more learning factories were built up in industry and academia. In this paper, the basic concept of learning factory will be described with emphasis on experience at the Faculty of Mechanical Engineering, Computing and Electrical Engineering (FSRE), University of Mostar. FSRE has started an initiative of the LF in faculty's premises. In this paper, the LF at FSRE regarding past, the current and future states of infrastructure, space and equipment are presented. Also, the phase of the LF product definition and selection and its connected manufacturing process is described. The future steps of FSRE LF are presented in the end.

Keywords:
Learning factory, Manufacturing education, Lean manufacturing, Competency development

1 INTRODUCTION

Manufacturing enters a new era, where novel life-long learning schemes need to keep up with the rapid advances in production-related technologies, tools, and techniques [1]. Considering the importance of manufacturing as a wealth-generating activity for any nation, the promotion of excellence will become a strategic target in the years to come. Manufacturing education will comprise a major driver towards that direction [2, 3].
For developing employees' competencies for manufacturing environments, traditional teaching methods show limited effects [4]. Therefore, new learning approaches are needed

- that allow training in realistic manufacturing environments;
- that modernize the learning process and bring it closer to the industrial practice;

- that leverage industrial practice through the adoption of new manufacturing knowledge and technology;
- that boost innovation in manufacturing by improving the capabilities of young engineers, e.g. problem-solving capability, creativity or systems thinking capability – talent based innovation is the number one driver of manufacturing competitiveness [5].

One promising approach for the effective development of competencies is the learning factory concept [6]. In this paper, the basic concept of a learning factory will be described with emphasis on experience at the Faculty of Mechanical Engineering, Computing and Electrical Engineering (FSRE), University of Mostar. FSRE has started an initiative of the LF in faculty's premises. In this paper the LF at FSRE regarding past, current and future state of infrastructure, space and equipment is presented. The phase of LF products selection is described and fields of education within the learning factory. Future steps of FSRE LF are presented in the end.

2 LEARNING FACTORY CONCEPT

2.1 History

The term "learning factory" was first established in 1994, by the Penn State University, United States, who received a grant to develop a "learning factory. It referred to an interdisciplinary hands-on engineering design approach with strong links and interactions to the industry. This program run by Penn State University won the National Academy of Engineering's Gordon prize for innovation in Engineering in 2006. Since then, the use of learning factories has increased, particularly in Europe [7]. Another less famous, more industry-focused approach was established in the late 1980s in Germany with the "Lernfabrik" (German for "learning factory") for a qualification program related to Computer Integrated Manufacturing (CIM) [8, 9].

Since then, the rapid increase of learning factories happened in Europe and worldwide. The rapid increase of funding made available and the high success of the learning factories stimulated the academic world and became a topic of general conversation, which lead to its popularity as a research topic. The numerous research efforts have produced a variety of topics, ranging from the validation of the success of learning factories, to design and implementation methodologies, improvement, and expansion processes [7].

2.2 Definitions

There are several definitions of a Learning Factory that may be found in the literature. The first known definition of a learning factory [10] describes a facility for product and process realization that can be used for academic education. Additional key factors include active participation of trainees and an agile environment. Abele et al. [11] base their definition on principally the same assumptions but emphasize the need for closeness to the reality of all aspects of such a facility in an authentic simulation. The teaching factory

concept of Chryssolouris et al. [12, 3, 13] connects the real factory with the classroom using advanced information and communication technologies (ICTs) for bi-directional knowledge exchange. The result of an investigation of more than 25 learning factories, Wagner et al. [14] fortify the postulation of authenticity and changeability of the factory environment and claim the suitability of learning factories for different target groups as well as the purpose of test and transfer of theoretical knowledge to the industry. With the intent to identify a methodical approach for developing action-oriented, competency-based learning factories, the definition of Tisch et al. [15] focuses on a systematic configuration of the learning environment. The members of the Initiative on European learning factories [16] agreed on a comprehensive definition with regard to realistic processes and the didactical concept. Sihn [13] differentiates between physical and virtual settings of learning factories and includes both types in his definition. Further definitions cover partial aspects [17, 13, 9]. Within the CIRP CWG (Collaborative Working Group) numerous explicit and implicit definitions of the term "learning factories" were identified, analyzed, and compared, in order to strive for a common understanding. The definitions are summarized in the CIRP Encyclopedia:
"A Learning Factory in a narrow sense is a learning environment specified by processes that are authentic, include multiple stations, and comprise technical as well as organizational aspects, a setting that is changeable and resembles a real value chain, a physical product being manufactured, and a didactical concept that comprises formal, informal and non-formal learning, enabled by own actions of the trainees in an on-site learning."
Depending on the purpose of the learning factory, learning takes place through teaching, training and/or research. Different didactical approaches are used, especially active and blended learning. Participants will benefit from interactive hands-on experiences and experiential, team-based learning involving students, faculty and industrial participation enriches the educational process and provides tangible benefits to all [18]. Also, LF offers a high potential for blended learning setup, where the learning factory serves as a meeting place and application scenario [19].
Consequently, learning outcomes may be competency development and/or innovation. An operating model ensuring the sustained operation of the LF is desirable. In a broader sense, learning environments meeting the definition above but with a setting that resembles a virtual instead of a physical value chain, or a service product instead of a physical product, or a didactical concept based on remote learning instead of on-site learning can also be considered as learning factories [20].

2.3 Product in LF

Like real factories, LFs also needs to define and have at least one product that will be produced. In general, two ways of finding a suitable LF product are recognized [19, 21, 22].
Industrial products available on the market are chosen (and possibly simplified didactically) with the intention to complete the learning factory configuration

(targets, technical system, etc.). Learning factory products are designed individually to complement the learning factory configuration. Fig. 1 compares the traditional product design process (a) with possible

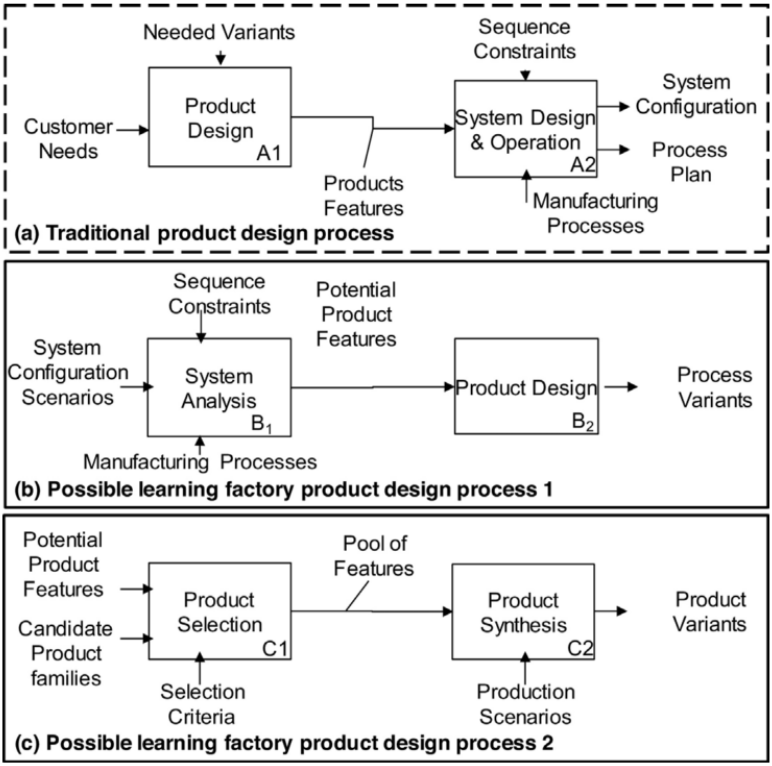

Figure 1: Comparison of traditional and LF product design process [22, 23].

LF product design processes (b, c). Additionally, several approaches dealing with specific design questions are recognized. Kaluza et al. [24] describe an approach to design scaled-down LF environments. Here, the focus lies on the exact modeling of the technical system in order to make sure that the scaled-down setting has the same characteristics (regarding energy efficiency in this case) as the life-size equipment. Also, it is mentioned that existing approaches focus on the design of learning factories for education and training. Tvenge et al. [25] see potential in the use of learning factories by opening it to a broader approach like the modern workplace learning framework [26], which allows learning in a continuous, on demand, autonomous, social, and on-the-go manner [9].

According to Wagner et al. [22], the product design requirements for the iFactory are different from requirements for traditional products. Table 1 gives an overview of these differences. A traditional product and its attributes are determined by the intended function of the product. Thus, the production processes including production equipment and logistic means as well as the production environment are defined by the product attributes. In contrast to this, possible products for the iFactory are determined by the attributes of the production environment. That means the product characters such as weight, shape, complexity, structure, dimensions, etc. have to fit the pre-determined capabilities and constraints of the learning factory. These capabilities and constraints are given by the installed manufacturing processes, production equipment, and logistic means.
As in every LF, in the FSRE LF, the characteristics of the LF product need to contribute to participants in the acquisition of competencies. As presented in the next chapter, based on the product, participants can obtain different skills from design, machining, assembly, welding, warehouse management and also other organizational skills such as lean management, continuous improvement etc.

Table 1: Differences between traditional and LF products [23].

	Conventional Product	Product for Changeable Learning Factories
Production environment	Influenced by product	Influences product
Production processes	Influenced by product requirements	Pre-determined
Product parameters	Determined by functional requirements	Determined by capabilities and constraints of production system
Objectives	Fulfill market & customer requirements & needs	Fit and support capabilities of the learning environment
	To be sold and to realize profit	Best possible achievement of educational and research content
Product Features	Real product	Simplified model of a real product
	Fulfill determined function	Best possible support of learning factory & its purposes
After usage	Reused, recycled or disposed of	Re-used in many process cycles.

3 FSRE LEARNING FACTORY

At the Faculty of Mechanical Engineering, Computing and Electrical Engineering, University of Mostar, the initiative of development of a Learning Factory has started in January 2018. Based on the good experience of partner faculties and universities the decision was made in that direction.
The faculty has applied on the project co-financed by European Union and implemented by GIZ and received a certain amount of funds for the project ´Increasing Competitiveness of Small and Medium Enterprises through Creating Business Associations and Establishing a Learning Factory´, within the EU ProLocal programme.
The faculty is the project leader, other partners are 9 local metal and plastic industries (SIK d.o.o. Mostar, Škutor d.o.o. Mostar, TT Kabeli d.o.o. Široki Brijeg, TEM Mandeks d.o.o. Široki Brijeg, Feal d.o.o. Široki Brijeg, Bilton d.o.o. Grude, Weltplast d.o.o. Posušje, Miviko d.o.o. Posusje and Femis d.o.o. Posušje), the city of Široki Brijeg and Posušje municipality.
The role of the faculty in the project, in addition to the role of the lead applicant, is the development of the concept of a learning factory in collaboration with enterprises and development of curricula and support to enterprises in the field of education and research. The role of enterprise in the project is a contribution to the development of lifelong learning curricula and the transfer of knowledge in the field of practical training in the LF. The role of the local community is to support the construction of infrastructure, fostering better cooperation between the academic community and SMEs, as well as raising awareness of innovation among citizens through activities and workshops on the project. The faculty is at the point of writing this article at the stage of defining the product and manufacturing process for the FSRE learning factory.

3.1 Current state

The faculty already has a part of the infrastructure for the LF concept. Through the project ´Increasing the competitiveness of the company in the metal sector through the introduction of the lean tool and the establishment of the Lean Competency Centre´ the infrastructure from the lean area will be partially developed. One of the additional objectives of this project is the establishment of the basic concept of the FSRE Learning Factory with the maximum use of existing equipment and infrastructure, in cooperation with the faculties from Germany and Croatia, local companies that are project partners and the local community. The realization of this project will create a platform and initial preconditions for joint action in the field of education, research, and training in the real environment.

Space and equipment

The current state of machinery at the FSRE is not on a satisfactory level - most machines are over 50 years old or not in operation. The plan is to get rid of unnecessary machines and to bring those that are still in function in the best possible condition. The workspace area is around 250 m^2. The workspace also needs to be renovated (floor, walls, electric installations, etc.). Currently, the construction work on the workshop premises (facades, doors, windows, floors and the like) and the work on the analysis of a new layout are done. It is planned to use some of the software to create the factory's internal layout (visTable, Autodesk Factory Design Utilities, CATIA).


Figure 2: Current state of workspace and machines (inside).

Figures 3 and 4 show the current state of the workspace from the outside and the future look of the workshop after the works.

Infrastructure
At FSRE, in addition to equipment and space as the initial preconditions for the LF, it also has a certain infrastructure that can fit into the entire LF concept.

Information system
FSRE has knowledge, experience and the required infrastructure for ERP and CRM business information systems to support the entire LF concept. As part of the information systems lab there exist various sensors, accompanying microcomputers (Arduino, Raspberry Pi and similar) and PLCs required for automation.

Product design and development
Regarding product design and development, FSRE has a long tradition and knowledge (CAD software, 3D printers, 3D scanner, and other necessary tools/methods).

Production
Here the production stands for material, product or semifinished product processing. The faculty has educated personal and some of the equipment for machining and welding.

Figure 3: Current and future state of the workspace (outside).

Lean tools and methods

Through the other project ´Increasing Competitiveness of Enterprises in the Metal Sector through the Lean Tool Implementation and the Establishment of the Lean Centre,´ a lean center consisting of people, infrastructure and curricula for further education in the lean methodology is established. The faculty has many years of experience in implementing lean tools in companies from the region and very good cooperation with higher education institutions and institutes that are also involved in introducing lean to other companies/ organizations.

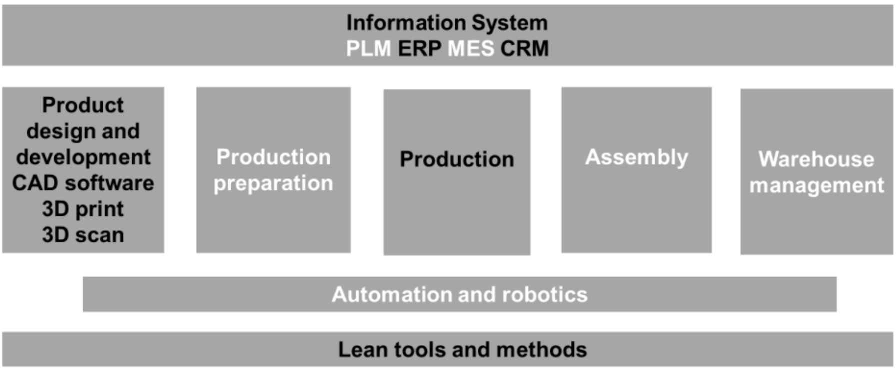

Figure 4: FSRE Learning Factory structure.

3.2 Future state

As shown in the Fig. 5, the entire concept lacks information systems elements (PLMs and MESs), production preparation, assembly, and warehouse management. The faculty has a plan in the near future to supplement these elements. We are already in the process of purchasing assembly sites (warehouses) – Fig. 8, which will be equipped with a system that will enable the automation of the assembly and storage process ("Pick by light" system – Fig. 9).

For automation and robotics, the faculty already owns certain equipment (mobile robots and PLC controllers), but it is planned to purchase a robotic hand that will enable automation of the production process.
FSRE did not use the methods for development of LF layout. The reason is that current workspace and surrounding industry is on a low level regarding the industry, which is also analyzed by the INSENT project research [27], which presented that the Croatian economy is on level 2.15 with regard to Industry 4.0. In future FSRE plans to develop an LF layout design using different tools and methods.

Figure 5: Assembly workplaces with supermarkets (left) and pick by light system (right) [28, 29].

3.3 FSRE LF product

As already mentioned in the chapter before, product selection is determined by the attributes of the production environment. FSRE has analyzed its production environment together with partner companies from metal and plastic sector and also by visits to different learning factories in Europe (Darmstadt, Bochum, Reutlingen, Friedberg, Split). After several workshops and meetings, two products were chosen: scissors and a lifting platform. The aim was to choose one "simple product" and one more complex.
Currently, the first two pieces of scissors were produced. It was first modeled in Solidworks and then a 3D prototype was printed. After that, two "real" pieces were manufactured. Also, in an ERP system, the whole technological documentation for production is prepared.
The other product, the lifting platform, is in the phase of design. Other steps regarding manufacturing documentation, production preparation need to be done.

3.4 Education at FSRE LF

The vision of FSRE LF is to provide education services for its student and company employees in different fields. It will be integrated into the curriculum of undergraduate and graduate study of mechanical engineering, especially

at the Department of Industrial engineering and management. This means that LF will be available for bachelor, master and doctoral theses, professional study theses and other research or professional work.
Since the FSRE has a good experience in lean engineering education, it is planned to adopt those educations in the LF environment, where the participants would participate close to the real environment. Some of the training would be in lean tools such as 5S, Kaizen, SMED, Continuous improvement, Poka Yoke, Value Stream Mapping, Kanban etc.

Figure 6: 3D model of scissors and 3D printed model of scissors.

4 CONCLUSION

As already mentioned the competencies of the employees are one of the most important things in adoption to different challenges in a production environment. The education system, in cooperation with economy and government, need to continuously work on raising the quality of student's and employee's competencies. One example of that is a learning factory concept. In this paper, the basic concept of a learning factory is presented, regarding its history, different definitions, and selected products. Further, the current and future state on FSRE LF is described regarding space, equipment, and infrastructure. In the end, the FSRE LF products and the planned education for students and company employees are described. In the future, FSRE needs to purchase necessary equipment to fulfill the LF concept with missing elements, develop layout of the LF, and to define production process of the selected products.

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The proceedings of the 8th International Conference on Production Engineering and Management, held between October 04 and 05, 2018 at the OWL University of Applied Sciences, collect the works carried out by professors, lecturers, researchers, graduates, and students of the OWL University of Applied Sciences, Lemgo (Germany), the University of Trieste (Italy), as well as experts from other European universities and from industry. The main aim of the eighth 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 topics of the conference, therefore, include not only production technologies and management in a narrower sense, but also new aspects of direct digital manufacturing, lean management, supply chain design and management, along with different topics of high interest for wood processing and furniture production and revolutionary developments in modern industry.

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