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INTERNATIONAL CONFERENCE ON COMPETITIVE MANUFACTURING

COMA'16

PROCEEDINGS

Resource Efficiency for Global Competitiveness

27 – 29 January 2016
Stellenbosch, South Africa

Organised by
Department of Industrial Engineering
Stellenbosch University

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International Academy of Production Engineering

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International Conference
on
Competitive Manufacturing

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About CIRP

CIRP was founded in 1951 with the aim to address scientifically, through international co-operation, issues related to modern production science and technology. The **International Academy of Production Engineering** takes its abbreviated name from the French acronym of **C**ollege **I**nternational pour la **R**echerche en **P**roductique (**CIRP**) and includes ca. 500 members from 46 countries. The number of members is intentionally kept limited, so as to facilitate informal scientific information exchange and personal contacts. In a recent development, there is work under way to establish a CIRP **Network** of young scientists active in manufacturing research.

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Foreword

Welcome to this sixth in South Africa International Conference on Competitive Manufacturing hosted by the University of Stellenbosch and organised by the Department of Industrial Engineering.

In a small world where global trade is the new driving force conquering countries and continents alike, international competitiveness is becoming the ultimate challenge of the new millennium. It requires high quality products manufactured with state-of-the-art technologies at low cost under the assumption of highly efficient operations management as well as clear corporate goals and strategy. This in turn is facilitated by and dependent on improved engineering training, education, and relevant applied research, fueled by active interaction between academia and industry.

The main objective of COMA '16, the International Conference on **Co**mpetitive **Ma**nufacturing is to present recent developments, research results and industrial experience accelerating improvement of competitiveness in the field of manufacturing. The 90 papers and presentations invited or selected to be delivered at the Conference, deal with wide aspects related to product design and realisation, production technologies and systems, operations management as well as enterprise design and integration. The worldwide participation and range of topics covered indicate that the Conference is truly a significant meeting of people striving similar aims. The event is an additional opportunity for communication between paper authors and attendees, which undoubtedly will serve as a further step towards exciting developments in the future. It also provides ample opportunities to further exploit international collaboration.

The Chairmen and the Organising Committee express heartfelt thanks and gratitude to the Members of the International Programme Committee, who have given their help and expertise in refereeing the papers and will chair the plenary and technical sessions during the Conference, as well as to the authors for participating and ensuring that the high standards required on an International Conference were maintained. These thanks and gratitude are extended to our highly regarded plenary speakers.

The Chairmen convey sincere thanks to the conference sponsors for their generous support, which made this event possible.

The International Academy of Production Engineering (CIRP) is gratefully acknowledged for the scientific sponsorship given to the Conference.

Finally, the tremendous effort of the Organising Committee is appreciated. Grateful thanks are due particularly to the Conference Secretariat for ensuring the success of COMA ’16.

We hope that you will find the Conference interesting and stimulating!

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Table of Contents

Plenary Session: Advanced Manufacturing – State-of-the-Art

Plenary Session: A Way Forward

Session A2: Innovative Concepts in Tooling Design and Implementation

Session A3: Biomedical Engineering

Session A4: Product Design and Optimisation

Session A5: Innovative Manufacturing Approaches

Session B3: Machining of Advanced Materials

Session B4: Advances in Metrology and Inspection

Session B5: Intelligent Manufacturing Concepts I

Session B6: Intelligent Production Systems

Session C2: Advances and Challenges in Logistics

Session C3: Modelling and Simulation

Session D2: Learning Factories

Session D3: Industry 4.0 - The Internet of Things

Session D4: Enterprise Engineering Tools

Session D5: Human Interface

PLENARY SESSIONS

Session P1: Advanced Manufacturing – State-of-the-Art

Session P4: A Way Forward

Digital Adaptive Production of Turbomachinery Components

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Abstract
The Digital Adaptive Production is generally seen as one of the big potentials within the fourth industrial revolutions. In this connection keywords such as Cyber Physical Production Systems, networked production or self-optimizing machining processes are often used. But what does Digital Adaptive Production actually mean? This article identifies the four essential fields of action which are the foundation for a Digital Adaptive Production. The connection between the modelling of the production processes, the alignment of model results using sensor systems, and the reaction on deviations by means of process controls are explained. Finally, an outlook is presented discussing the potentials of Big Data methods and novel technology-based data models and their relevance for an Adaptive Manufacturing.

Keywords
Adaptive Production, Big Data, Simulation, Data Coupling, CAx-Technologies

1 INTRODUCTION

The fourth industrial revolution is characterized by a digitalized and networked production and aims at Cyber-Physical Production Systems (CPPS), i.e. interconnected autonomous and self-optimizing production machine tools manufacturing intelligent and highly individual products. The so called “Industrie 4.0” therefore demands a holistic consideration of production systems and process chains. The flexibility of manufacturing systems and the capability to be self-optimizing go hand in hand with virtual models of the production systems allowing for simulation-based planning and testing sequences prior to the implementation in reality. The developments around the digital adaptive production are mainly driven by industry sectors focusing on especially complex products and high quality requirements. One of the most prominent examples here is the aerospace industry: The products in this field feature extreme geometries such as complex thin-walled blade structures or deep and highly curved cavities requiring latest machine tool technologies and complex manufacturing processes. Furthermore, components are manufactured out of advanced high-strength materials which are difficult-to-machine, which – as a result - cause rapidly changing manufacturing conditions due to high process loads, cutting zone temperatures and therewith tool wear rates. Finally, the products have to meet extraordinary safety standards in order to be approved for service. The following section presents the main fields of action which are required to enable Digital Adaptive Production in challenging industry sector such as turbomachinery manufacturing.

2 FIELDS OF ACTION FOR A DIGITAL ADAPTIVE PRODUCTION

In general there are four fields of action that can be identified as the essential pillars of the Digital Adaptive Production, see Figure 1 below. These are

- the coupling of models and software tools for process optimization,
- the linkage of real process data with simulation models,
- big data approaches which can be used in order to efficiently handle large data volumes and provide methods for correlation of key values to process conditions, and finally
- technology based data models for adaptive manufacturing, which are able to manage the virtual path going in parallel with the product in its entire life cycle.

The first field in this scope focuses on process modeling and the coupling of models with software tools for process optimization. When it comes to manufacturing complex products and components, the modelling of the process behavior is especially difficult and pure analytic model approaches are either not available or able to describe the actual situation with sufficient accuracy. Therefore, simulation models are usually employed which are able to handle complex three-dimensional and instationary problems. The specific process knowledge gained through these simulation-based models is an essential asset being used to efficiently design manufacturing processes [1]. On the downside, however, the uncertainty of the obtained model results increases with growing complexity, requiring costly verification experiments.

This leads to the second field of action within the scope of the Digital Production, addressing the link between simulation-based models and real process data being acquired by sensors. The sensors in the production environment provide a feedback about the deviation between the nominal situation predicted by the simulation model and the actual situation in reality. To this extent, the combination out of real sensor information and the nominal value allows for a monitoring.

By closing the loop, a control system can be realized, enabling the reaction on deviations between prediction and measurement. Nowadays, machining processes are often controlled e.g. to prevent tool breakages due to sudden overloads or to guarantee a constantly high material removal rate despite steadily changing tool engagement conditions. Employing conventional control systems, instabilities are likely to occur as soon as process loads change rapidly [2, 3]. This however is often the case when complex component geometries such as deep and highly curved cavities are machine using five-axis machining processes [4, 5]. In this regard model predictive control systems utilizing simulated process knowledge present a big potential to operate an efficient production [6].

The information provided by the sensor systems plays a fundamental role for the calibration procedure where the results, which are computed on the basis of the process model are brought into alignment with the measured reality. Here, two different directions of impact can be identified significantly influencing the quality of the information which is available about the system: On the one hand, intelligent or smart sensors allow for a raw data pre-processing – which also can include process models – and thus provide a higher information quality. On the other hand, the number of sensors and therewith the information density in the system to be described can be further increased. In this connection, the information is not necessarily an output of external sensors being deliberately brought into the production environment; rather the machine tool itself acts as a sensor system where the information being processed in the machine tool control (e.g. drive torques or axis movements and deflections) is gathered and utilized.

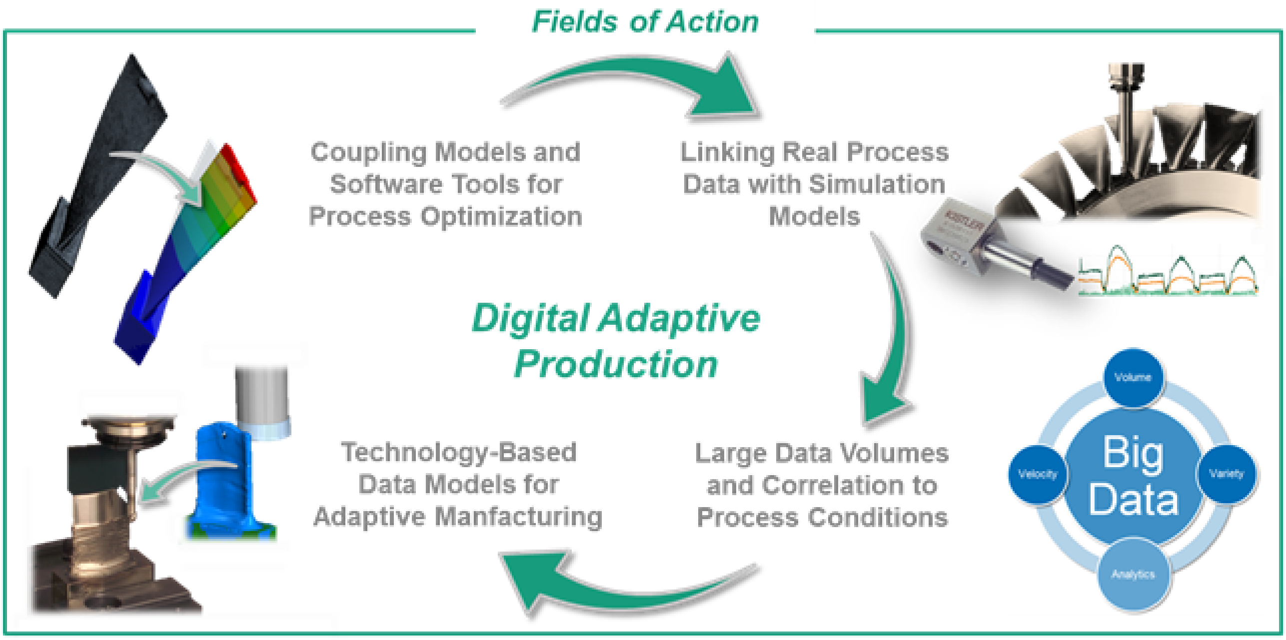

Figure 1 - Fields of Action for the Digital Adaptive Production

This leads to the third field of action dealing with Big Data methods which include the handling of large data volumes and the correlation between sensor information and different process conditions. Taking into account the fact that a high density of reliable information is available about a regarded system it arises the questions, if the model can be generated using the actual measured data. In doing so the procedure of time-consuming and costly development of a substitute model would be skipped and every product or component would possess an own model built upon real process data which was by nature verified and validated. The potential of Big Data analytics - that in essence can be regarded as statistical correlation methods - could in fact be confirmed to indicate valid correlations when tested in connection with manufacturing processes [7]. Yet the importance of the appropriate meta-information, required for an explicit data assignment could be underlined. Even for a single value representing the process force acting on a cutting tool can require a considerable amount of meta-information such as the correct position of the tool in a five-axis milling process, the engagement situation of the cutting edges in the workpiece, information about the material properties etc. In order to successfully tackle these challenges a close cooperation between different disciplines is necessary in order to connect process knowledge and data management competences.

The last field of action concentrates on technology based data models for adaptive manufacturing. The product life cycle begins with the design phase and proceeds with the planning and simulation of the manufacturing process before actual production. Especially in the aero-engine sector products are not scrapped after service, but undergo a repair process before entering a further cycle in service [8, 9]. Parallel to the product life cycle a wide range of data emerge within the different stages, see Figure 2: The digital life of the product starts with knowledge that is gained along this path. This learning process is then used for an improvement of next generation products.

3 SUMMARY

Digital Adaptive Production presents an enormous potential to operate more efficient production processes due to the flexibility of manufacturing systems and their capability to be self-optimizing. Within this scope, four major fields of action could be identified. In a first step, precise process models are necessary in order to shorten up conventional

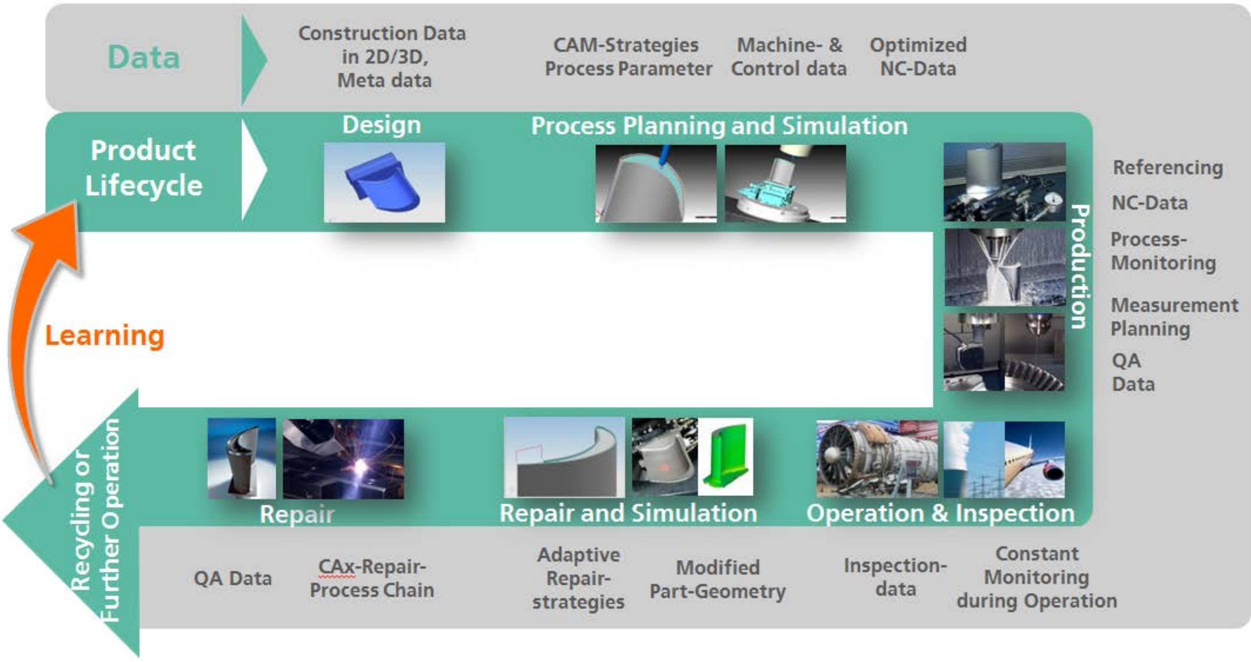

Figure 2 - Technology-Based Data Models for Adaptive Manufacturing

design data such as CAD datasets, later CAM datasets are generated including tool path planning throughout the entire manufacturing process where vital technology information is stored. The CAM planning and the simulation using a machine tool model usually results in optimized NC datasets which are required in the production sequence. During manufacturing referencing data, process monitoring and measurement data for quality assurance are generated. Inspection and condition monitoring data come up during service and in the repair phase models of the present component are generated using reverse engineering processes in order to acquire the actual part geometry and initiate the repair process involving a similar data flow as it occurred within the initial manufacturing cycle [10].

Recent developments focus on data formats that are able to track and store the entire virtual product life cycle in parallel to reality and therewith create a so called “digital twin” or “digital shadow”, which can be regarded as an adapted to the situation reduced data set. This enables most efficient adaptive production and repair processes and furthermore allows for closing the loop by feeding back

iterative manufacturing design sequences and allow for an effective product life cycle up to the actual production. With growing complexity of the process models the uncertainty increases as well and a corresponding calibration process including real process data is inevitable. The comparison between nominal model values and measurement data makes a process monitoring possible and allows for a process control by closing the loop and reacting on deviations in a next step. A big potential for controlling complex systems with steadily changing conditions is the model predictive control utilizing model-based estimations for an improved control performance. A better image of the actual situation can be obtained by employment of intelligent or smart sensors providing a higher information quality or by an increased number of sensors providing a higher information density. In this relation Big Data Analytics can be used in order to handle the emerging large data volumes and even generate process models established on the basis of statistical correlation methods. This bears the potential that each product possesses an individual model being establsihed out of real measured process data. Recent efforts focus on further on technology-based data models for adaptive manufacturing which aim on tracking and storing a digital twin or digital shadow of the product along with the life cycle of the real component.

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5 BIOGRAPHY

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Generation of Predictable Surface Integrity State of Machined Components

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Introduction

The state of surface integrity [1] strongly influences the functional performance of components. Functional properties such as wear resistance [2] and/or fatigue strength [3] are dependent on surface and subsurface properties such as roughness, material micro structure, hardness, and residual stresses. Thus, the prediction of the surface integrity resulting from machining a certain workpiece material is of high relevance for academia and industry.

Common understanding and definition of surface integrity

The term surface integrity was first coined by Field and Kahles in their CIRP keynote paper from 1971 [1]. They stated that "Surface Integrity can be defined as the entirety of inherent and enhanced properties of a surface. It involves a study and control of surfaces that can be generated by machining or other operations". The state of surface integrity can have a decisive influence on the functional performance of manufactured parts. Though Field and Kahles introduced an extensive list of possible alterations by machining, from a mechanical engineer's point of view particularly the modifications of sub-surface properties like hardness, material structure, and residual stresses are of major interest.

Historic developments

Manufacturing of the early days was a geometry-driven task. Conformity to the design tolerances was the major issue [4]. Later, in the 1960s the importance of surface topography was identified as being highly important for a variety of functional properties. Researchers like von Weingraber, Peters, Whitehouse and others paved the way for a better understanding of surface topography and their analysis and assessment [5]. Then, in the 1970s the air- and space technologies became drivers for a deeper analysis of sub-surface properties and their influence on the functional performance. CIRP members like Field, Kahles, Tönshoff and Brinksmeier, König, Peters and others delivered important contributions to the state-of-the-art [1, 6]. Once the importance of surface integrity was proven, researchers and industry were very interested in the prediction of sub-surface properties after machining, a reliable prediction turned out to be very difficult, however. In the late 1970s an interesting approach was presented by Malkin and Guo [7], who were able to define a critical specific energy for a grinding process. The application of these considerations allowed for the prediction of possible undesired material modifications like grinding burn. This work has to be highlighted, as the authors succeeded in correlating an energy-based threshold for material modifications with process parameters in grinding. Later, in the early 1980s Brinksmeier proved that in grinding the changes of residual surface stresses can be correlated to the specific grinding power [8], though the heat partitioning within the process was not known. In this regard, Stephensen [9] and Komanduri [10] contributed with remarkable work in the late 1990s by analyzing the energy dissipation in grinding and orthogonal cutting by calculating the heat partitioning [9]. Then, in the early 21st century, Heinzel refined the state-of-the-art-concepts by successful correlations of grind-hardening results with specific power and heat exposure time [11].

Since then, more research was done but still, a prediction of the state of surface integrity after machining is almost impossible. This was also confirmed within a collaborative work of CIRP from 2009-2011. Though participants had the free choice of a machining process and machining parameters, it was not possible to achieve the desired state of surface residual stress [2].

Machining and sub-surface properties

For selected processes, numerical [12, 13, 14] and analytical [15] models allow for a choice of suitable process parameters without iterative or experience-based preliminary experiments. However, even these approaches are based on the input of quantities such as geometries and the process-kinematics and require the subsequent assessment of the changes of surface and subsurface properties (e.g. modifications of the microstructure, and/or hardness alterations, as well as residual stress state). However, the selection of process parameters based on a desired state of surface integrity of a component (inverse problem in manufacturing) is an unsolved problem until today.

It is assumed that this knowledge gap results from the common process-oriented view that has been prevailing in the scientific analyses in which predominantly the resulting workpiece material modifications were correlated with the machining parameters. The internal material loads, e.g. loading stresses, strains, temperatures, and temperature gradients, which actually lead to the observable modifications, are rarely or even not at all under consideration. As a consequence, the acquired correlations are mostly process-specific and cannot be transferred to modified or even other processes.

Process Signatures to predict the state of surface integrity

A material-oriented view which focusses on the mechanisms leading to workpiece material modifications during machining processes, like the concept of process signatures, could resolve this problem. The idea of developing a new understanding regarding the correlations between the material loads during a manufacturing process and the resulting material modification by means of Process Signatures was first presented in 2011 [16]. Process Signatures correlate the material modifications with the internal material loads which lead to modifications by activating mechanisms such as yielding and/or phase transformations. The utilization of Process Signatures should enable a comparability of apparently different machining processes, assuming that similar internal material loads will lead to similar material modifications. Figure 1 indicates a causal sequence from a material's point of view which is independent from the chosen machining process. The modifications of the surface and subsurface properties are characterized by one or more so called state variables such as hardness, residual stresses or microstructure.

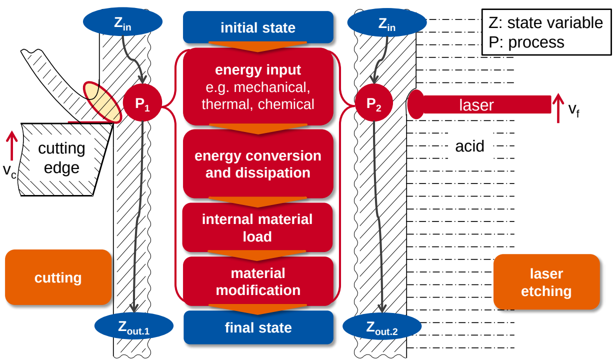

Figure 1 - Causal sequence of material modification caused by two processes with different action principles [17]

On a more practical level, the conversion of thermal, mechanical and chemical energy during machining processes causes a specific internal material load and thus, changes of the workpiece material. The energy conversion can be characterized e. g. by the forces and temperatures leading to strain distributions and temperature gradients within the material. For a grinding process, for example, the application of the moving heat source model based on Jaeger and Carslaw [18] can be used to assess the thermal loads caused by energy input and dissipation. The strain and stress distributions in the subsurface layers can be can be calculated from the mechanical loads (forces) e. g. by using the Hertz formulas [19].

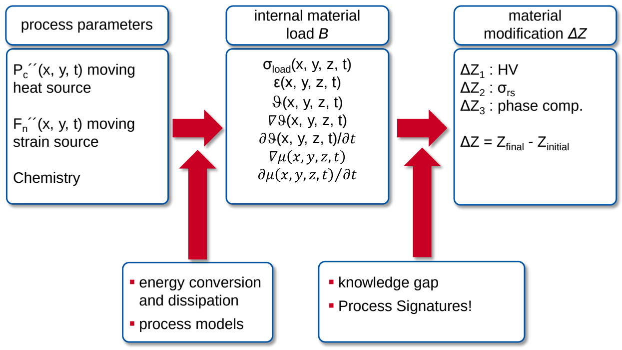

Figure 2 - Transfer functions correlating process parameters and internal material loads as well as internal material loads and material modifications (Process Signatures)

To achieve an advanced level of correlation between the internal material loads and the material modifications, the fundamental mechanisms leading to a change of one or more state variables must be understood. Fig.2 shows that the key to establish Process Signatures is based on sufficient knowledge on the correlations of internal material load and resulting material modification. In addition, it has to be taken into account that the effects of internal material loads lead to material modifications on different scale levels. Consequently, the identification of Process Signatures implies the knowledge of scale effects.

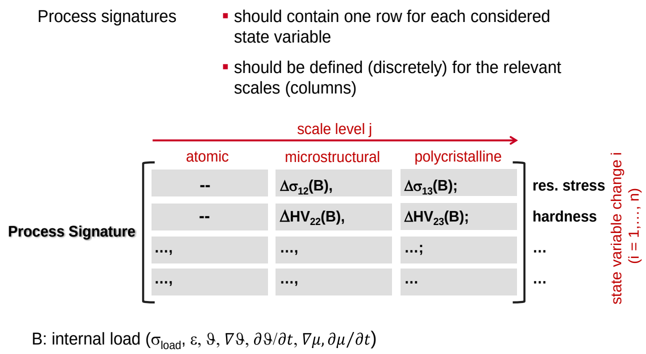

Figure 3 - Notation of Process Signatures

As indicated in Fig.3 the signature of a process can be described as a collection of specific loads during a process which have to be correlated with the changes of material modification (state variables, including depth information) at different scale levels [17].

The changes of state variables have to be correlated with the process loads. Not all of these loads are easy to assess during the process. For a systematic approach, the empiric results must therefore be affirmed and supported by numerical and analytical models. The main areas of research needed to identify and apply Process Signatures lay within three fields:

- Manufacturing technologies (processes),
- Metrology (process loads and changes of state variables),
- Modelling and simulation (correlation of process parameters, process loads and changes of state variables)

Within a Collaborative Research Center (SFB/TRR136) based at the University of Bremen, the RWTH Aachen, and the Oklahoma State University at Stillwater, currently the challenges of measuring and simulating the internal material loads as well as the analysis of material modifications are of predominant interest.

An example for a solely mechanical loading is shown in Fig. 4. The internal loading of steel (austenitized X210Cr12) - determined by FE-simulation- was enforced by deep rolling, the resulting hardness changes on the macro scale represent the material modifications including yielding and a strain induced martensitic phase transformation. Here, the hardness profile correlates well with the internal load stresses. As expected, the hardness changes when the yield stress of the material was reached.

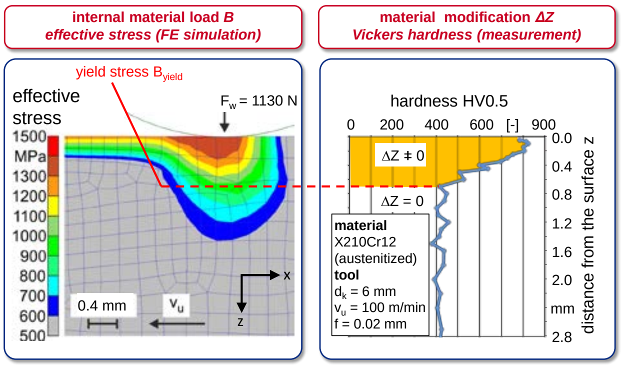

Figure 4 - Internal material loading and material modification in deep rolling

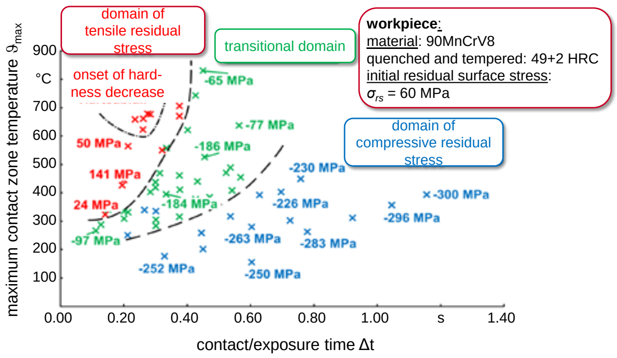

Figure 5 - Correlation of internal material load (temperatures at fixed contact times) and material modifications (residual surface stresses) in surface grinding

Another example is taken from surface grinding of case hardening steel, Fig. 5. The temperatures in the contact area have been measured by a special grinding wheel equipped with infrared temperature measurement [20]. In the chart the temperatures are plotted versus the contact time (heat exposure time). The resulting material modifications have been grouped according to residual stress levels. Though heat partitioning has not been considered so far, the predominant influence of the temperature on the residual stress is obvious.

It becomes evident that much more work will be needed to acquire a full picture of material internal loading and material modification as preconditions to set up process signatures. But already now a deeper insight into material behavior in machining has been reached.

Outlook

In order to solve the inverse surface integrity problem in machining it will be necessary to correlate the desired material modifications with the process parameters applying the knowledge of internal material loads. It is planned that the material loads will be calculated from the desired state of surface integrity by using process signatures. By this procedure it should be possible to derive the necessary process parameters from a set of envisaged surface layer properties, Figure 6.

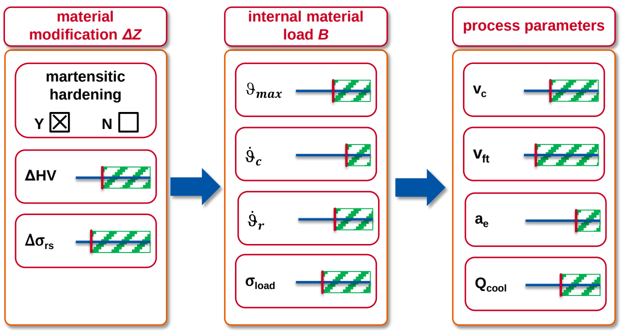

Figure 6 - Exemplarily application of process signatures to solve the inverse problem of surface integrity in machining

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Biography

Professor Dr-Ing habil Ekkard Brinksmeier was born in 1952 in Lage, Germany and studied mechanical engineering at the University of Hannover, Germany. After receiving his Dr. -Ing degree in mechanical engineering in 1982 he worked as Chief Engineer at the Institute for Production Engineering and Machine Tools (IFW), Director Prof. Hans-Kurt Toenshoff, Hannover. He finished his habilitation in 1992, became a full professor at the University of Bremen, and holds the chair of manufacturing technologies. Furthermore, he is Director of the Foundation Institute of Materials Science (IWT) and the Laboratory for Precision Machining (LFM). His scientific interests and research areas lie in the field of advanced manufacturing processes with special focus in the areas of grinding, ultraprecision machining, development of sensor-integrated tools, development of advanced metalworking fluids, and the generation of functional surfaces by machining. Prof Brinksmeier is Fellow of CIRP, serving currently as its President, as well as Fellow of SME. He is past president of the European Society for Precision Engineering and Nanotechnology, eu**spen**. Prof Brinksmeier has received several awards, most notably the CIRP F.W. Taylor Medal and the DFG Gottfried Wilhelm Leibniz Award, which is the most prestigious German research award.

Additive Manufacturing on the Way to industrialization

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Abstract
Additive Manufacturing is today considered as shooting star beneath the manufacturing processes. The expectation is nearly infinite as only additive manufacturing is expected to finalize a work piece from the scratch. But there is quite a way to go until additive manufacturing processes really become industrially mature. Some of the ever growing group of additive processes will never reach the threshold of industrial application. Quality assurance, material properties, surface quality, geometric accuracy, economy, buildup rate and embedding in process chains are challenges still to be solved. On the other hand additive processes introduce a relief of nearly all restrictions in manufacturing and thus enable a freedom of design, which makes those processes attractive. But nevertheless the economic potential still is not fully exploited. Quite a number of examples underpin the great opportunity given by additive processes. Necessary developments for the future of additive manufacturing are identified.

Keywords
Additive Manufacturing, Quality Management, Accuracy, Manifold of Materials, Trends

1 INTRODUCTION

Since the invention of Stereolithographie (SLA) in the 1980s by Hull [1] Additive Manufacturing (AM) slowly developed and became a Hype since 2011 in industry and manufacturing research such that people forgot that there is manufacturing research besides AM. But the development in that times was meant for prototyping, for the generation of 3-dimensional objects as geometry specimen for developing a better 3-dimensional awareness of the objects. It was not intended to use SLA-parts for direct utilization in industrial products. "Rapid prototyping" was at that times the correct terminology for those processes. With the invention of Selective Laser Sintering (SLS), Selective Laser Melting (SLM) in the 90ies and 2000 respectively new technologies that were capable to produce parts which had properties at least on the threshold of making them applicable in industrial mechanisms. The first term coined was rapid manufacturing, denying, that milling in terms of manufacturing of small series was much faster than for instance SLM. The common properties of this group of processes for the creation of parts is the assembly of geometries from a huge number of individual elements in a layerwise manner without utilization of tools. The layerwise manufacturing lead to terms like "3-D-printing" or "3-D-manufacturing". Both actually are misleading terms, as 3-D-printing is one of the approximately 100 different layerwise manufacturing processes, where at least the binding material is applied in a liquid phase and is cured or dried afterwards. "3-D-manufacturing" is also a misleading terminology, as all manufacturing, might be with the exception LIGA 3-D, especially form milling as archetype of subtractive manufacturing. Aproximately since 2009 "additive manufacturing" was coined by ASTM-F42 generally adopted for industrial layerwise manufacturing technologies. But AM is not really a new technology, it is a new discovery of technologies. Actually by no definition it is possible to exclude building with bricks from the group of AM technologies, which is a technology dating back thousands of years in the Babylonean culture. Figure 1 shows the contrast between subtractively and additively manufactured buildings. But also welding technologies have since long ago been exploited for additive buildup of structures.

Figure 1 - Subtractive manufactured monolithic St. George in Lalibela, additively manufactured brickbuilt St. George in Wismar.

AM technologies belong to original forming technologies according to DIN 8580, which in comparison to all other original forming technologies does not need any model or mould, which makes it ultimatively flexible. But it is necessary to recognize, that there is hardly any original forming technology, which produces ready to use parts, only in the high flying visions of additive manufacturing ready to use parts come out of this group of original forming technologies.

2 INDUSTRIAL PROCESSES

About 100 different AM process variants have in the meantime been invented from which 3-D-printing is one subgroup. One main difference between those AM processes is the materialgroup to be used and thus ISO 17296 [2] as first criterion distinguishes between AM processes for metals, polymers, ceramics and biological materials. As an example from ISO 17296-1 a morphological box for metal processing AM processes is shown and electron beam melting (EBM) shows the utilization of the morphological box.

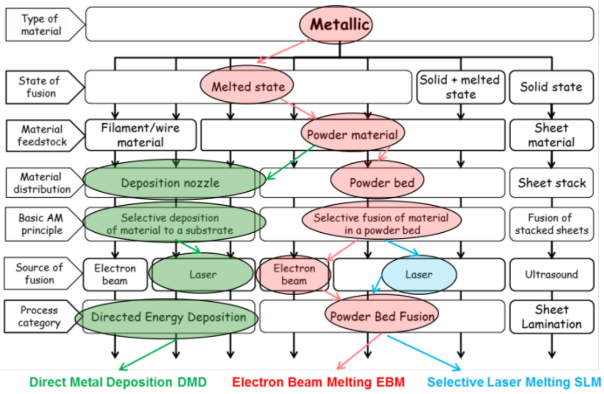
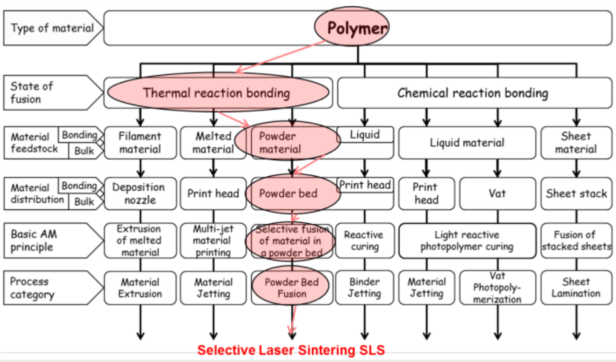


Figure 2 - Morphological box for AM for metals ISO 17296-1.



3D printing: fabrication of objects through deposition of material using a print head, nozzle or another printer technology

Figure 3 - Morphological box for AM for polymers ISO 17296.

As the layerwise manufacturing processes stem from rapid prototyping it is worthwhile to discuss, which processes are able to produce parts or even raw parts ready for utilization in industrial products. Material properties and part geometry are created with AM processes at the same time. Therefore essential criterion for industrial applicability is that the parts exhibit material properties comparable to material properties achieved by conventional process chains. Interesting properties are mostly stiffness, strengths as yield, rupture, fatigue, creep, ductility esp. elongation at break, isotropy, resistivity against aging as for instance pointed out in [27, 31, 32]. Especially the latter excludes all processes, that solidify the material by photons, because those materials cure under UV light from the sun after manufacturing. Besides reaching mechanical properties also the reproducibility of results and achievable accuracy play a major role in industrial applications, which is discussed lateron. For processing polymer parts only SLS and for parts with reduced requirements to a certain extend also FDM (fused deposition modelling) is used. But already FDM fails in realizing sufficient strength in the direction orthogonal of the build plane. For metal parts by far mostly SLM is used, to a certain extend also DMD (direct metal deposition), which both are laser processes. While SLM is powder bed based and the layers thus necessarily are orthogonal to the gravity direction, DMD can realize arbitrary layer shapes and thus is ideal to be combined with conventional manufacturing methods as premachined parts can be used as a basis to build up complex geometries, for instance impellers can be made by turning a cone and additively build up of the airblades. Examples are shown in [26]. If the surface between conventional prefabricated part and additive addition is a plane, tha combination of the two processes is also possible for SLM and is frequently used for tool and die parts. The choice of other energy sources here also yields processes valid for part manufacturing. EBM works with electron beam in a powder bed instead of the laser. And also DMD where instead of a laser a MIG torch is used to melt material is an industrially valid AM process. Secondary criteria are utilized to distinguish between those processes. SLM-parts today achieve the best accuracy and surface quality, but are limited in the buildup rate to approximately 100 to 200 g per hour (25 cm^3/h for steel) and laser spot depending on the material being processed and also to a certain extend on the complexity of the structure being built. The limitation stems from the coating step in between laser steps and is also due to the fact, that introduced heat must be dissipated and the powder bed acts as good isolator. EBM achieves approximately double built up rates (400g/h for TiAl6V4), but the surface quality is much less. Laser DMD achieves even higher built up rates up to several kg per hour and the surface quality is still less as pointed out in [6]. One reason is, that there is no sequential coating of the surface, input of new material and solidification is done in parallel.

3 MATERIALS

A major step towards industrial application of additive manufacturing was the freedom of choice of material of those AM processes that today are industrial manufacturing processes. Lucky for SLS is the fact, that it is restricted from material choice to one of the most important polymeric materials for engineering parts, namely PA. PA12 and to less extent PA11 is the most used polymer in SLS as reported by [28]. DSC-curve (differential scanning calorimetry) shows the main success factor of PA 12. This material has according to [29, 30, 31] below solidification temperature a small gap until the onset of crystallization. In this gap the solidification of the powder material takes place, while the building area is kept on temperatures above the crystallization point and only upon final cool down of the whole part crystallization takes place.

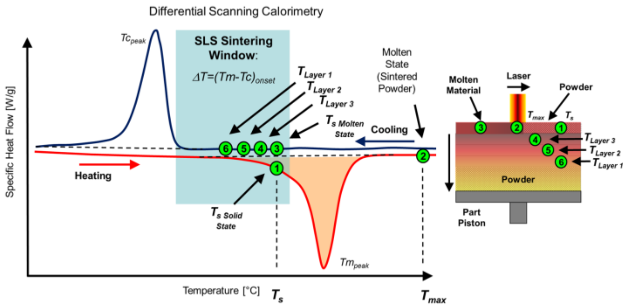


Figure 4 - DSC curve for PA 12 showing the gap between solidification temperature and onset of crystallization, [4].

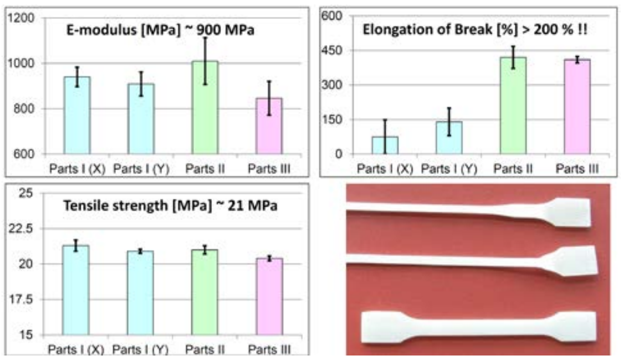


Figure 5 - Properties of ICOPP polypropylene Copolymer depending on powder ageing (new powder Parts I, aged powder Parts II, III), [34].

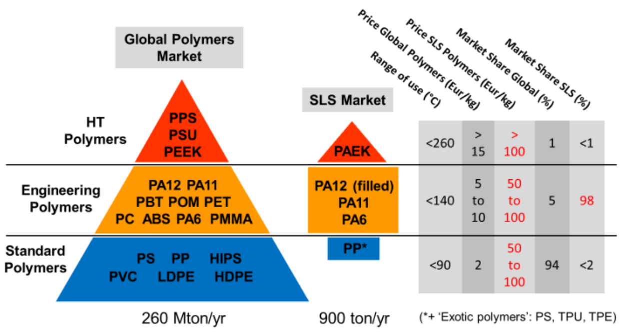


Figure 6 - Utilization of polymeric materials in general and compared to SLS, [35].

The advantage is that the crystallization does not stop on the weld pool boundaries of individual layers, which drastically enhances the strength in direction vertical to the layer plane. Comparison between the strengths achieved in FDM and SLS given by [33] shows, that this is the decisive success factor for SLS with PA 12. The search for new materials for SLS therefore goes in the direction of materials with a gap between solidification and crystallization temperatures.

- Cr-Steels: [7-10]
  X46Cr13 (1.4034), X3CrNiMo13-4 (1.4313), X2CrNiMo17-12-2 (1.4404), X5CrNiCuNb16-4 (1.4542), 1.2709, 18 Maraging 300 etc.
- Tool steels:
  X3NiCoMoTi18-9-5 (1.2709)
- Light metals: [11-17]
  AlSi12, AlSi10Mg
  TiAl6V4 (3.7165)
- Ni-based alloys: [18-24]
  In 625, In718, In738, Haynes 230 MarM247
- Co-based alloys: [25]
  CoCr28Mo6
- Material cominations
- Alloying by blending
- MMCs with different filler geometries

Table 1 - Metallic material utilized in SLM

- Laser power [W]
- Scan-speed [m/s]
- Pitch feed [µm]
- Layer thickness [µm]
- Number of end vectors
- Build direction (polar)
- Location in build area
- Temperature distribution
- Powder: distribution of particle size, aspect ratio
- coating device: achieved density

- Spec. line energy [J/mm]
- Spec. aerial energy [J/mm²]
- Spec. volume energy [J/mm³]

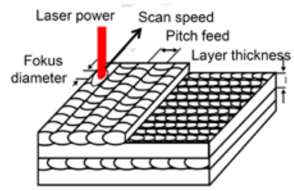


Table 2 - Most important influence parameters for SLM

Figure 5 shows the properties of a newly developed Polypropylen (PP) copolymer. Leading property of PP is its large elongation at break, and only upon good connection between the layers this property is reproduced in SLS. Figure 6 shows the fairly low number of SLS processable materials as comparison to polymer utilization in total, which shows the clear demand for research to enlarge the amount of variety of materials available.

Somehow different is the situation for metal parts. All materials that can be welded in general can be processed in SLM or DMD. But today's machines are strictly limited in process technology. The research in design of the microscopic process of melting and resolidification, which is responsible for all the faults limiting the AM process technology, the measurement of process time temperature phase change diagrams and their application for AM is still at its very beginning. Table 1 shows a selection of material that have been reported to be manufactured in SLM. Again the requirement is to achieve material properties, that are similar to those achieved for metallurgically generated material like with casting, forging, etc.. Depending on the application the demand is for static, dynamic strength or resistivity to creep. Naturally the toughness plays an overall important role. Prior to utilization of a metal in AM a process window, a range of powder and process parameters needs to be identified, within which the required properties of the material is achieved.

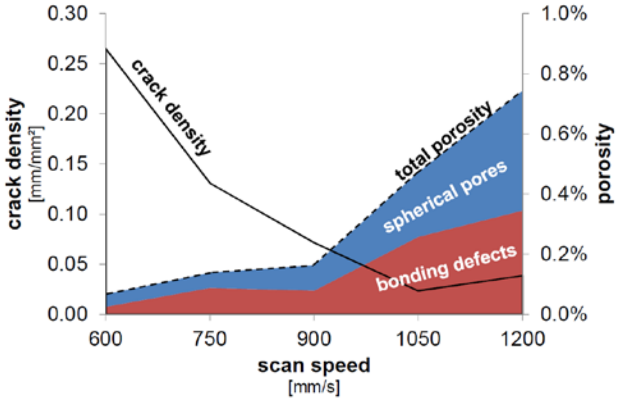


Figure 7 - Influence of scanning speed on faults in In 738 for constant laser power [36].

Detrimental effects are pores, flaws, bonding faults, hot and cold cracking. Most important parameters to establish are listed in table 2. Here the different specific energies play a significant role, but obviously power and scanning speed are independently of relevance. Figure 7 from [36] gives an insight into the behaviour of Inconel 738 in dependence of scanning speed at constant laser power.

The mechanical properties depend on the microstructure realized by AM. As the cooling is due to the small melting pool very fast, fine grain sizes typically develop. But it is also realized, that the crystallographic structure of the surrounding solid material is continued into the newly solidifying melting pool, which means that the grain structure is typically columnar with axis perpendicular to the build plane and the columnar grains range over several layer thicknesses as presented in [36]. Because of the fairly small grain size typically the static strength is slightly larger than for metallurgically generated material, for the yield strength the Hall-Petch relation applies. The dynamic behaviour depends largely on the number of flaws and pores generated by the highly dynamic melting pool. As pointed out by [37] fatigue strengths typically are 20% lower than for metallurgically generated material. Figure 8 shows further typical behaviour found: SLM generated material is anisotropic. In the direction perpendicular to the build plane the fatigue strength for over 100000 cycles is higher and in the direction of the plane with scan direction changed by 90° from layer to layer below 100000 the strength is higher. It is interesting to note, that the difference between unmachined specimen and polished specimen is not that large as might be expected from the roughness values of the surface, which is good news for all AM manufacturing, where post processing of the surface becomes difficult.

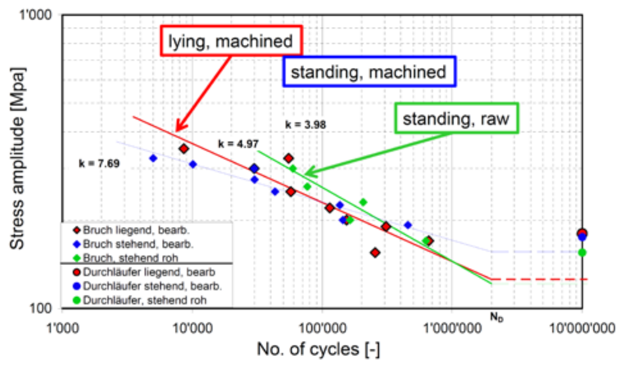


Figure 8 - Wöhler lines for AM processed specimen of In718.

It is important to notice, that the specification of alloys is often insufficient for SLM. In [19] was found that the permitted bandwidth of different elements is too large for SLM, which means that within the tolerances there are powders that can be processed and those that cannot due to development of hot cracks or pores with the same parameter set. As in other manufacturing technologies it seems to become necessary to develop special alloys and suitable alloying tolerances that allow easy and reproducible AM.

For ceramics the variety of available materials is still more limited and the development of AM in ceramics is still in its very beginning. Up to now no really densely sintered ceramic part has been achieved. The problem is the cold cracking due to thermal stresses out of the strongly inhomogeeous temperature distribution. AM is used to produce green parts, where the ceramic particles are mostly bonded by some polymeric binder. The parts are then postprocessed by degassing and sintering. But even with this strategy really dense parts were not possible. The densest ceramic parts up to now are made by Deckers et al. [3] in the process chain: AM, degassing and presintering, afterwards infiltration of nano slurry into the still open pores and dense sintering. And some hope is placed on an additive process, which is designed similar as liquid phase sintering, where powder with higer and with lower melting temperature are mixed and the lower melting particles are molten selectively with the laser.

4 FREEDOM OF DESIGN

Essential difference between subtractive and additive manufacturing is that subtractive manufacturing has to cope with disturbing contours, material of the part that restricts the accessibility of the tools. AM per principle has no disturbing contours, because the volume above the build plane is not yet solidified. This is the source of nearly infinite geometrical freedom, freedom of design. Besides the possibility to generate mechanisms directly by AM and without any assembly Figure 9 shows some parts, which emanate from the goal of lightweight construction. Figure 10 in addition to the freedom of design shows a comparison between AM and conventional manufacturing in terms of cost structure for a small series of parts, depending on geometrical complexity.

Figure 9 - Collection of typical lightweight structures manufactured with SLM.

Because the lightweight structures of Figure 9 clearly cannot be manufactured by milling irrespective of the amount of money to be invested, the cost curve for conventional manufacturing has a pole. But even left of the pole, there is an intersection point, a break even, indicating, that left of this point conventional manufacturing is advantageous, while on the right side AM should be applied, given that the quality of the parts manufactured by AM and conventionally is sufficient for the application.

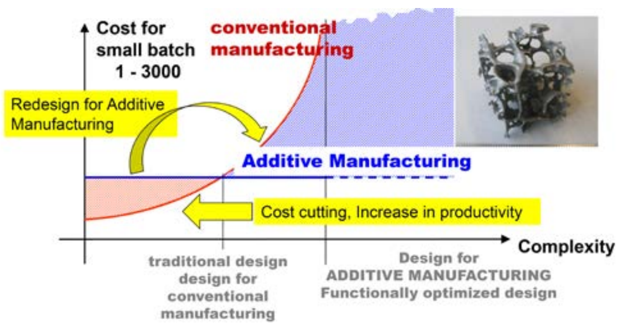


Figure 10 - Complexity for free: Comparison between SLM and conventional subtractive processes.

Current research in AM processes tries to enhance productivity and applicability of AM. The latter means amelioration of quality with respect to reliability, accuracy, roughness and material properties. This means a shift of the break even towards the left side. On the other hand to fully exploit the benefits of the AM processes it is indispensable to setup research and education in design for AM. Opposite to all other design for X, design for AM means encouragement to abandon design restrictions, trained for conventional manufacturing processes.

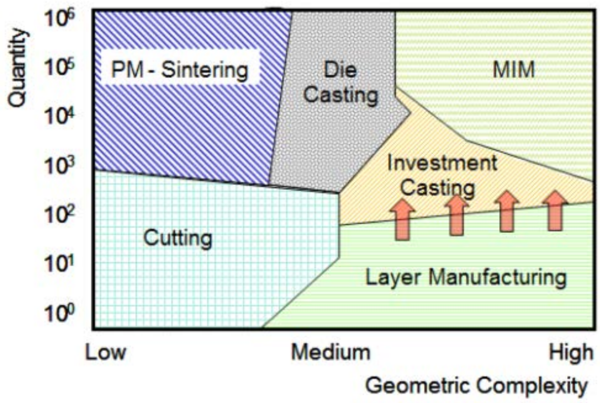


Figure 11 - Fields of application of different processes, adapted from [38]

An idea of the applicable processes for different batch sizes and different complexity gives Figure 11, where the break even limits between different technologies are shown. Figure 12 shows different parts, that are really manufactured for industrial application with AM due to cost savings within the whole process chain. Either costs for tools and dies could be saved or the assembly of the final product could be reduced due to increased and with AM manufacturable complexity of the parts or the part was just cheaper than the conventionally manufactured part. This latter holds true for internally cooled turbine blades with the buildup rates of modern SLM-machines.

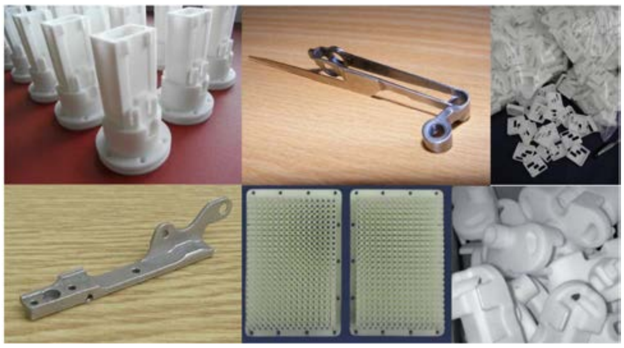


Figure 12 - Collection of parts manufactured and used in industrial assemblies.

Very interesting for AM are repair tasks, which either can be fulfilled by DMD on the geometry of the part to be repaired or in case of turbine blades by manufacturing of coupons to be inserted into the damaged area of the blade as was patented for instance in [39]. An efficient process chain starts with the scanning of the worn out part geometry and its interpretation, followed by the setup of the repair strategy and in the end a conventional milling grinding or polishing step. Due to the reason that all worn out parts look different, the described process deals with highly individualized geometry, which is always beneficial for AM processes.

5 ACCURACY

AM technologies are original forming processes and as such incapable to deliver finished parts. Functional surfaces need to be post treated, mostly by conventional processes. Therefore it is worthwhile to establish an uncertainty budget, which possibly gives some hints for necessary research.

Source of error	Value [µm]	exp- [µm]
Position accuracy laser	5…10	<5
Positioning accuracy build platform	5	1
Discretization error layer thickness	50	<10
Praticle size (discretization limit)	40	5
Process space size (melt pool width)	50…100	20
Variation of process space	10	5
Thermal distortion, warp	1000	50

Table 3 - Error budget of AM processes for SLM in steel, typical values today and expected [41, 42, 43, 44]

Table 3 gives an example of such an uncertainty budget for SLM with steel powder. The table also gives some estimates on possible future ameliorations of the process. Position accuracy of the laser and positioning accuracy of the buildplate are for industrial AM machines surely not the limiting factors, as machines can be designed for similar accuracies as conventional processes. This is one major difference between real AM-machines and machines for home applications. Figure 13 from [57] shows that indeed for FDM machines the positioning accuracy is a topic, but this machine didn't cost more than 10000 $. Discretization errors as stemming from the processing of the geometry, triangulation, slicing can be reduced. Reduction of layer thickness at the same time reduces production speed, which is one of the shortcomings of AM anyhow. The layer thickness is limited by the powder particle size, which cannot be reduced infinitely, due to the powder handling problems and adhesive forces as pointed out in [45, 46]. More important and limiting are uncertainties stemming from the process. The melting pool size is somehow also a kind of discretization limiting the smallest size of geometry manufacturable. But according to [44, 47] the melting pool is not really constant in size, depending on scanning speed, variation of the part temperature and thus depending on the strategy, depending on the absorption behaviour and disturbances of the power supply due to fumes and smoke. The fume extraction, which for most machine manufacturers is treated just as a side product is nevertheless dominating the accuracy.

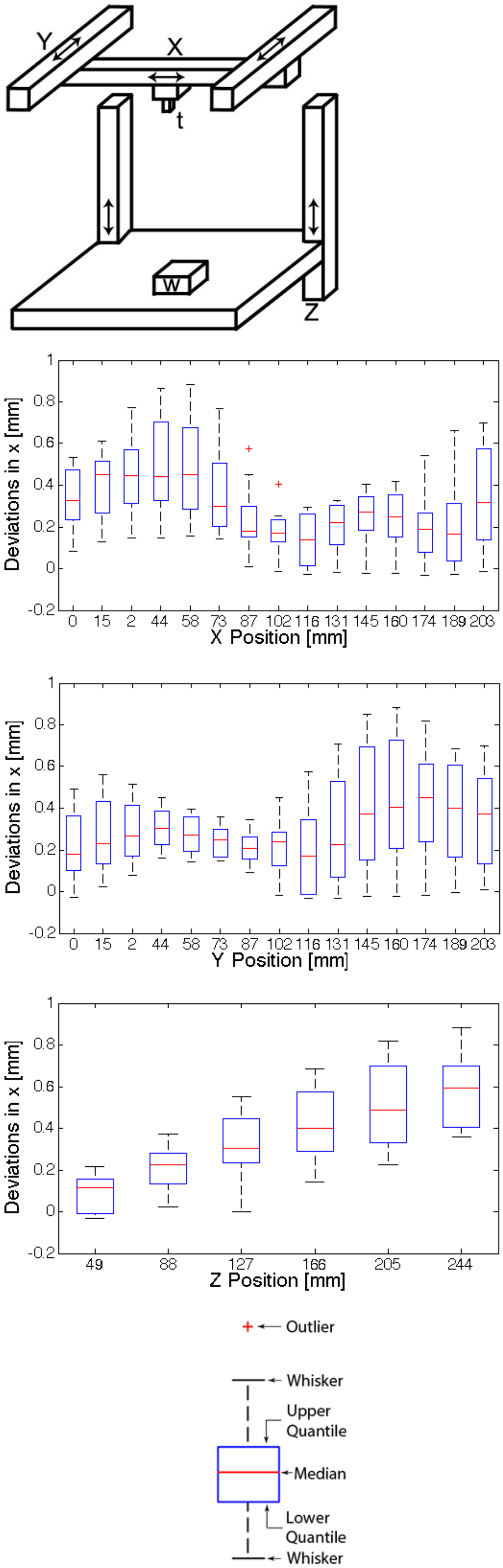


Figure 13 - Positioning errors for an FDM machine [57].

The largest and today mostly unmastered source of uncertainty is the development of internal stresses and upon removal from the build plate the released distortions of the parts. They might be even in the range of mm, depending on geometry and process strategy. To enhance the accuracy it is of utmost importance to predict and counteract the development of internal stresses. This is possible by designing the melting and solidification, pre- and post-heating strategy, which all can be realized during the AM process without necessity of postprocessing. The SLM process is a complex multiphysical problem. Therefore, several researchers have developed models to compute some of the main effects. Boley [48] calculated the laser absorption by metal powders during SLM. Gusarov [49] developed a different model for the interaction of a laser beam with a thin metal powder layer, giving insight into the effective thermal conductivity and absorptance of powders and packed beds. Bontha [50] provided a model to calculate the weld pool geometry during SLM, and Klingbeil [51], next to other researchers 52, 53], calculated the resulting microstructure. The modelling of the temperature field, internal residual stresses and distortions during SLM has been modeld by different researchers, such as Zaeh et.al [4], Hodge et.al [54], Papadakis et.al [55], Cloots et.al [56] with partially different approaches. Amado [5] was able to compute the distortions of SLS manufactured beams, taking into account the crystallization process according to Figure 4 Model based parameter optimization to master distortions might thus become feasible.

Strongly related to accuracy determining parameters is the achievable surface quality. According to [58, 59] important influence parameter is the powder particle size, a particle is either connected to the surface or not, which yields a surface roughness of R_z, which is in the range of the particle size. But the different surfaces, parallel to the build plane, parallel to scanning direction and orthogonal to scanning direction look different. In most cases a strategy is chosen, where the scanning direction is from layer to layer turned by 90°, which gives similar appearance to all surfaces but introduces as roughness determining parameter also the focus diameter and the hatch distance.

6 QUALITY

Manufacturing processes require strict quality management. Today the assessment and certification of the process is recognized to be the more efficient way for the quality assessment in comparison to the direct measurement the individual tolerated features. Especially if properties for instance material properties can only be verified by destructive methods the indirect quality control, monitoring of the process is indispensable. As material and geometry in AM-processes are generated at the same time, and process parameters influence as shown the accuracy as well as the material properties process monitoring is indispensable for lifting AM over the threshold of industrialization. Today the quality of parts made by AM still depends on the operator to a larger extend than for any conventional process. It is the large number of influence parameters and the lack of awareness of machine manufacturers towards the influencing parameters. Figure 14 shows for an SLS process the temperature distribution within the building area of an industrial SLS machine and the correlation to the Young's modulus and the ultimate tensile strength achieved in different positions of the building area. The amelioration of the quality requires to gain control over all the influencing parameters, which are as an example for SLS identified in Figure 15 as Ishikawa-diagram. All uncontrolled parameters increase the range of uncertainty of the process and broaden the width of scatter of the final results.

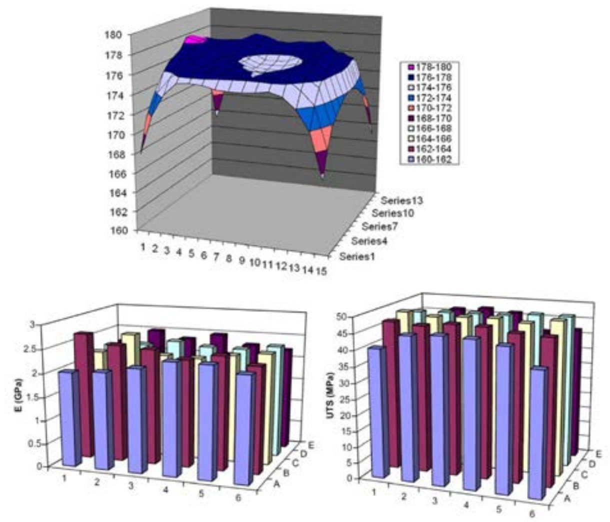


Figure 14 - Temperature distribution within the working area of an SLS machine and correlation with the achieved mechanical parameters, [60].

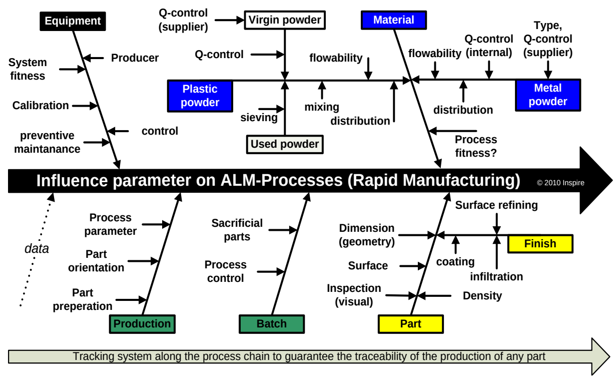


Figure 15 - Ishikawa diagram for the identification of influence parameters in SLS.

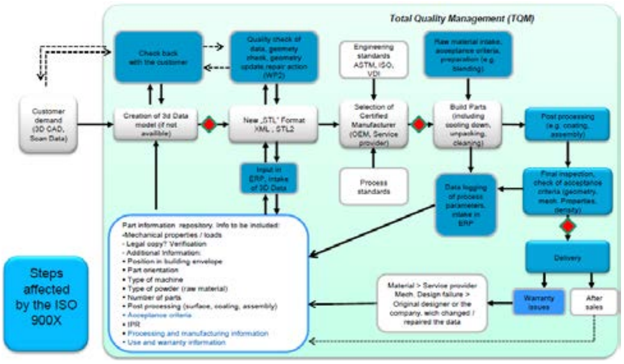


Figure 16 - Structure of a quality management system proposed by EU project Direct Spare, [61].

Figure 16 shows an example for a quality management system, which has been developed within the European project direct spare [61, 62]. It is important to note, that it is necessary to extend the monitoring of parameters along the whole process chain, the powder generation, powder handling, powder distribution and the AM process. Different powder geometry like aspect ratio, size distribution yields different results in the density of the powder layer and subsequential in the density of the final part.

7 TRENDS IN AM

As pointed out AM processes today are still on the threshold of industrialization. Designed mainly for rapid prototyping the move towards a real industrial additive manufacturing is a trend as such and the strongest motor of change for additive processes. All developments identified by market survey and discussed in the following have their roots within this main development.

Full exploitation of the design freedom offered by additive processes is still a mental obstacle for engineers who have been trained since decades for conventional manufacturing and recognize design opportunities which are today offered by AM as design faults.

As indicated most important requirement for industrial processes is their reliability and reproducibility. All parts manufactured on different machines and different operators need to be within tight tolerances. This necessitates standardization and the development of measures for quality management in AM processes. Those measures have to cover the whole process chain from powder manufacturing onwards to the finished part. It is clearly recognized, that the process monitoring as indirect quality control will play a major role, as pointed out by Mani [63]. It is today state-of-the-art using melt pool monitoring in SLM. Melt pool monitoring has initially been developed by Mercelis [64]. Craeghs [65] developed a framework for monitoring of the powder layer quality and melt pool; in the meantime other researchers also developed appropriate melt pool monitoring solutions [66, 67]. The number of decisive influence parameters is for AM processes larger than for conventional processes and to reduce the scatter of results, it is important to understand the determinism of the process and to keep the the parameters all under control. This implies a profound scientific understanding of the process.

To gain scientific process understanding important topic in research is the process simulation for AM. Possibilities are seeked to predict the development of the microstructure and the probability of pores and cracks and thus the material properties. It mainly implies a precise local modelling of the melting and resolidification. On the other hand accuracy is decisively influenced by the development of internal stresses, which can be mastered only by computation of internal stresses and model based strategy planning.

General problem of AM processes is the bad surface properties, which today mainly is mastered by elongating the process chain by post processing techniques as sand blasting, cutting and polishing. Problem is the limited accessibility of surfaces after the AM process, why possibilities are seeked to enhance the surface directly in the AM processes, which means before building up further disturbing contours. Direct milling or grinding after each or a number of layers is much easier for DMD than for SLM because of the powder bed, which is then stirred up. Such possibilities are offered by upcoming combi-machines, that are capable of AM and cutting processes. Also laser polishing is discussed in this respect.

Lacking accuracy and surface quality enforce the continuation of the process chain as already discussed. Combi-machines that offer AM and conventional technologies in the same motion frame are extremely flexible in the application of both process technologies but suffer from the high CAPEX. The machines need to be capable of pursuing the respective process comparable to single purpose machines, which means that the invest is not too far away from the invest in two single purpose machines, while one technology is always idle. For industrial application it is thus worthwhile to think on machine sequences with standardized interfaces, where the build platform for instance can be automatically handed over from the AM machine to the postprocessing machine and clamped there with the standardized interface. This means that automated AM machines will more and more appear on the market and as batch processes are today avoided as much as possible under the vision of one piece flow, continuous AM machines might come up in future. Also branch specific machines start to appear on the market because of different requirements. Machine development will focus more and more on specific fields of application and/or part types. Examples are medical implants, jewellery, and aerospace parts. Drivers for such developments are the general complexity and structure of a part including needed surface qualities and tolerances. Further aspects are the typical part volumes and the corresponding required lot sizes. It can be expected that in the nearer future specific hybrid AM-machines will be available, beeing capable of manufacturing metal parts up to a size of several meters, and in the hundred kg range.

The development of process windows is as discussed in chapter 3 essential prerequisite for qualitative good parts. Machines in future will have parameter presettings for all kind of different materials, which makes them easy to use. And as discussed before, new alloys especially developed for AM will shine up on the market.

Research in AM processes will increase the buildup rate, which makes AM still more attractive and shifts the break even towards higher batch sizes and simpler parts. Also accuracy and surface quality and material quality will increase in future due to concerted research efforts. All this opens up new part families for AM. Examples are ultralight weight parts, where only AM is capable to manufacture topology optimized geometries. Further examples are medical implants, jewelry, aerospace, power machines, mold and die. As AM machines are developed as general purpose machines, there is a development to access micro parts manufacturing as well as macro parts manufacturing by AM. Micro AM requires often completely new process technologies and thus also specialized materials like in 2 photon polymerization (2PP). Nevertheless metallic micro parts for industrial application is an open research field. Specialized machines for macro parts are developing right now. Again wire based technologies instead of powder technologies because of their higher material efficiency come into discussion and also non laser based technologies as MIG / MAG technologies come up because of their much cheaper process technology.

Last but not least a vast application field will be the whole biomedical sector. Driven by the strong individualization of implants AM has already a good standing in this sector, obstacle is the expensive FDA required for AM processes. Research goes into the direction of directly printing biological tissues or scaffolds for living material as for instance shown in [68].

To sum up there is still a bright future for industrial application of AM. But there is still a lot of work to do for AM to keep up with available understanding and capabilities of conventional processes. The visions are tremendous, which might give rise to some disappointments in the reality of AM processes. AM will gain quite some place in the concert of manufacturing technologies, but it is unlikely, that AM will be capable to replace one of the conventional technologies. But AM technologies might to some extend one day change business models of global manufacturing. It is necessary to recognize, that the full exploitation of the benefits of AM needs to start with a structural redesign of existing devices. This requires a new skill and education set on all levels of industrial value creation and especially in product development.

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9 BIOGRAPHY

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STREAM A

Product Design and Realisation

Session A1: Product and Process Modelling and Design

Session A2: Innovative Concepts in Tooling Design and Implementation

Session A3: Biomedical Engineering

Session A4: Product Design and Optimisation

Session A5: Advances in Additive Manufacturing

Framework to Develop and Evaluate Process Chains for Resource Efficiency

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Abstract
Continuous development of new, and the improvement of existing products yields a vast collection of concepts and prototypes. Such products do not yet necessarily have established process chains. An area therefore exists for the development of novel manufacturing process chains towards the production of such products. In order to select a process chain most suited to the user's needs, it should be evaluated with regards to the design space in which it is applied. This paper presents a framework to create and evaluate resource efficient process chains, with an application example in the context of integrated medical implants. To realize this aim, a guideline was developed to lead the user through the entire thinking process for process chain evaluation. An empty template provides the user with creative freedom to apply the included methods for idea generation. After creating process chain variations, an assessment of each is executed. An evaluation score ranks the process chains in order of suitability for its specific purpose.

Keywords
Process Chain; Framework; Process Chain Evaluation

1 INTRODUCTION

The creation of process chains is an important part of product development. The process chain directly influences the costs of the product along with the production time and other associated parameters. It also defines which and how much resources are necessary to produce the product [1]. The resources relate to all fields of the company, for example manpower, material or capital investments (business resources). In execution of the software however, resources are specific to user defined scales, be it industrial, small to medium, artisan, or private. Importance for efficient use of resources is evident from rising costs in all business sectors [2-4]. It therefore also requires focusing on resource efficiency when a new process chain is developed [4]. To improve a process chain's resource efficiency, new manufacturing technologies can be utilised. For example, with additive manufacturing (AM), the user is able to significantly reduce the material waste compared to conventional methods. Another advantage is the high geometrical freedom that allows for adding functionality to existing products [5]. Certain studies suggested enhancements for medical hip implants such as drug delivery channels to reduce infections and sensors to detect the loosening of an implant [6-8]. Therfore an application model is based on studies from Bezuidenhout *et. al.* [8, 9] who demonstrated a sustained antibiotic release profile from conceptual drug delivery features produced with AM for eventual incorporation into cementless hip stems. Most of these technologies, however, are not yet fully integrated into a process chain, because it is difficult to evaluate the process chains with new technologies to determine whether one process chain is more efficient than another [10]. Blanch et al. [11] and Mousavi et al. [3] described different approaches to evaluate or improve process chains, but these approaches are focused on specific fields, for example, mechanical parts or only energy consumption. Such approaches are not necessarily user friendly for any client. Therefore this paper proposes a generic guideline, along with a software program, for the evaluation of process chains with an approach that is centred on the user defined importance for each factor within the process chain under consideration. The software can also be implemented theoretically in a learning / teaching environment to elucidate inherent differences between manufacturing processes and why certain operations are better suited to specific process chains than others.

2 FRAMEWORK AND METHODOLOGY

The architecture of the framework is illustrated in Figure 1 which also graphically describes the methodology. The framework includes a guideline, represented by Figure 1 level A, to create process chains, and important indicators to serve as input parameters for the second part of the framework, the VBA (visual basic for application) Program represented by Figure 1 level B. Level C represents the final process chain which is the most resource efficient process chain for the customer's needs. In the first section of the Guideline the user has to specify the focus which to design for, *People*, *Planet* or *Profit*. The *Business Focus* considers social aspects along with environmental aspects and profit. The next step is to set the *Focus Areas* and

Requirements downstream below the *Business Focus*, shown in Figure 2. The different levels shown in Figure 2 (vertical light blue bars) represent the more detailed execution of the description order. In the most cases, not all requirements have the same importance to each user. For this purpose, all requirements receive a weighting during the application of the guideline. The weighting is created by using utility analysis. The batch size of production is a very important parameter when creating a new process chain for products, because it is the main indicator of production scale. If the user wants to produce large batches of a product, it is more important to have a short manufacturing time. With the tool the user can also consider that fact by creating the requirement production time and assigning a high weighting to it. The levels are then divided into sections based on the upstream dependency. The sections are represented by orange boxes in Figure 2. In these sections the user can subdivide a total of 100% according to the importance of each identified constituent in the section. The value for each constituent depends on its perceived impact on the process chain. The weighting for each requirement is obtained by multiplying the percentages left to right along each single path from business focus to requirement. In the second section of the guideline, the process chains are created (Figure 1 level A). It starts with the design of the part (Figure 1 No. 1), from that the manufacturing steps (MS) are derived and manufacturing methods (MM) are identified to realise these steps (Figure 1 No. 2). To gather all possible ways to realise the MS, the user should consider the question:

Which processes are able to execute the MS?

The next step in the guideline is the selection of material or a material combination for the product (Figure 1 No. 3). A brief literature survey is advised to find the proper material for your product, because new materials or alloys are continuously being invented and improved by certain companies and institutes [12, 13]. The user then has to ensure

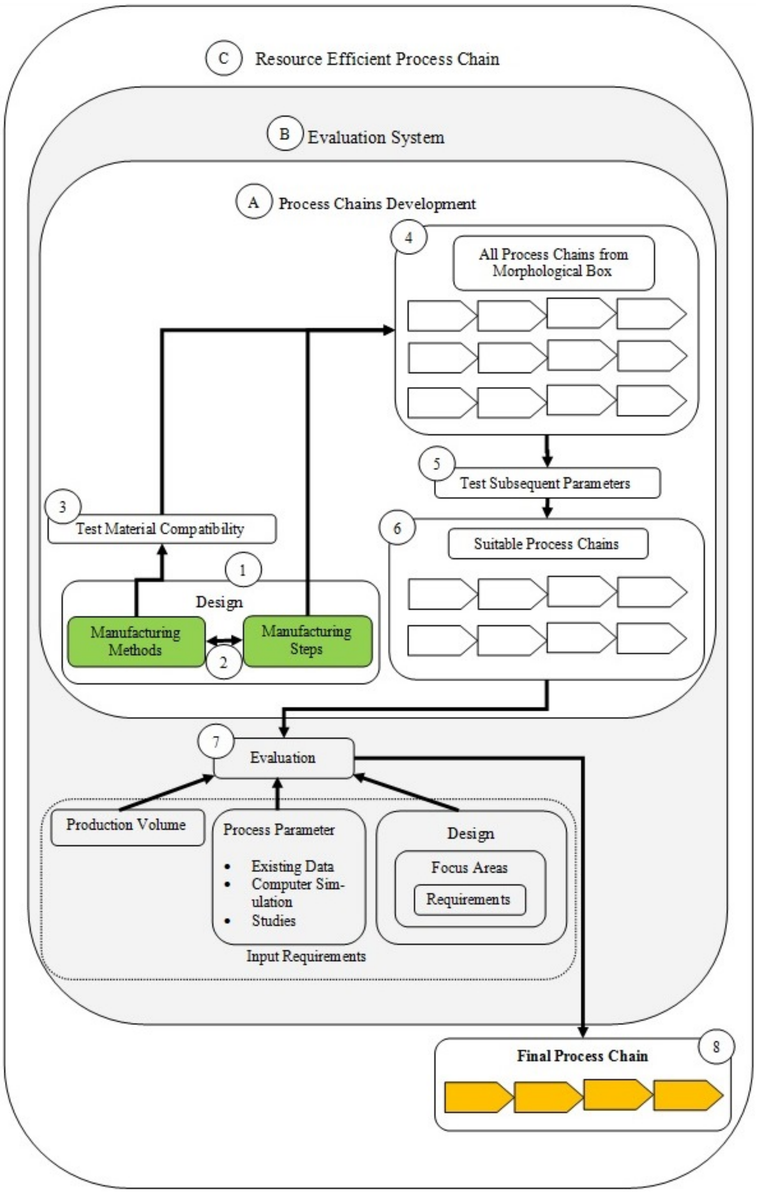

Figure 1 - Process steps to develop and evaluate resource efficient process chains

that each identified manufacturing method is compatible with the respective material. Lovatt et al. [14] termed it Processability and defines it as follows:

"The process must be able to modify, form or join the material in the required manner repeatably and reliably." [14, p. 218]

Based on experience, reports or data sheets, the user has to decide if the identified process is indeed capable to work the specified material. If it is not, it has to be deleted (Figure 1 No. 3). At this stage the design process should be in an embodied or detailed point. The reason is, when the product has many design changes during the whole process, the user can obtain misleading results. In the following section a morphological box is used to create different process chains, Ritchey [15] defines the morphological analysis as follows:

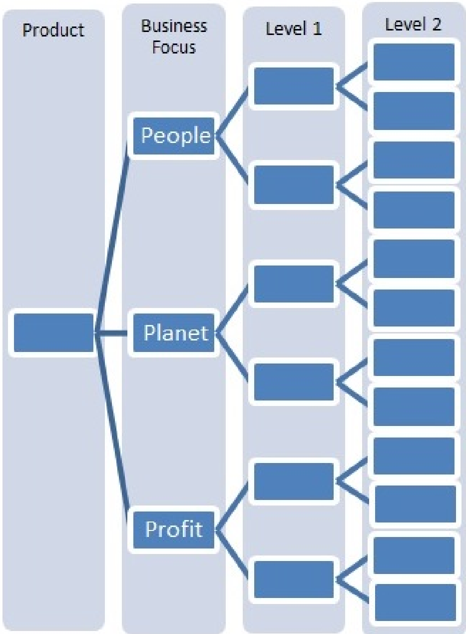

Figure 2 - Evaluation Hierarchy

"[…], general morphological analysis is a method for identifying and investigating the total set of possible relationships or "configurations" contained in a given problem complex." [15, p. 3]

For this purpose, a set of parameters is prepared. A range of relevant conditions is assigned for each parameter to find all the possible paths from top to bottom. The morphological box is then prepared for process chain development (Figure 1 No. 4).

The manufacturing steps that the user derived in Figure 1 No. 2 are the base of the morphological box, and each is entered into the first column. The remaining MM from No. 3 will fill the row behind the corresponding MS. When all possible methods are gathered, the MM are connected top to bottom to create the process chains (Figure 1 No. 4). This step yields a selection of process chains for evaluation, but it also can include unfeasible process chains. These unrealistic process chains are due to the sequence of processes, because some processes are not able to run in front or behind another one. For example, it is not possible to mill a section and use sandcasting as a downstream process. Process chains with these errors have to be corrected (Figure 1 No. 5). When the procedure is finished, only feasible chains remain (Figure 1 No. 6). These process chains need to be assessed with the program (Figure 1 level B). For reliable results, it is necessary to have detailed information about all the encompassed processes. For this purpose the user has to gather information in different ways. Data bases, computer simulations of the processes, and experience with the technology, or case studies can provide information. If all required information is collected, the program should be utilized at the next step (Figure 1 No. 7).

The program comprises UserForms with insert fields, buttons, charts and a flip down chart. It also provides assisting texts while working with it. The program is based on VBA coding as mentioned above and can work with up to 10 process chains and up to 20 requirements. After opening the program, the first UserForm provide insert fields for all requirements with units and the accompanying weighting created with the guideline.

The second UserForm aids the operator to insert all process chains. Execution of the code is performed by clicking the button "*Add new Process Chain*", which inserts the first process chain. After that, the customer has to write down the first name of the process and confirm the name by clicking "*Add process*". After confirmation, the field will be empty again and ready for a new process name. The user has to write down all of the processes for the first chain. When he has finished the first chain, he can go on and click again "*Add new Process Chain*" and repeat the steps. When all process chains are embedded in the program, the button "*Insert Data*" continues the program.

The UserForm "*Data gathering*" provides an insert box to enter all collected data for the process chains. It starts with the first process chain and the first process in this chain and also with the first requirement that the user entered on UserForm1. After pressing the *"Insert"* button, the program continues and moves along each row and each requirement. When all fields have received a value, the input box instructs the user to click "*Continue*".

The next UserForm shows the rating range used by the program for the evaluation process. With this Information the consumer can go on to the "*References and Goals*". In this UserForm the customer has to determine the minimum and the maximum limits of the evaluation range for each requirement. The user can decide to create own goals / limits or use an existing process chain as a reference and derive the limits, but the user has to ensure that the total amounts of each requirement is between those limits. The range is inserted by selecting the requirement from the drop down box and entering the minimum and the maximum values. The data is confirmed by clicking "*Save References and Goals*" to pass it to the program. This procedure has to be repeated until the last requirement has received its limits.

To finish the UserForm, the customer can continue to "*Show Results*" and a PDF sheet is created, level C in Figure 1. The Sheet contains the different scores for the process chains from the evaluation process. A bar-chart on the bottom of the sheet compares the scores from the process chains. With the PDF sheet, the customer can easily decide which process chain he should choose depending on these specific needs (Figure 1 No. 8).

3 APPLICATION OF THE FRAMEWORK

To demonstrate the functionality of the prototype evaluation program, a conceptual device without an established process chain has been identified in the form of a cementless hip replacement femoral stem with drug delivery features. Promising results have been obtained when conceptual features were evaluated [9]. A conceptual femoral stem encompassing such features is presented in Figure 3.

Figure 3 - Application model

Utilising techniques discussed for Level A in Figure 1, a variety of four processes have been identified based on the design and manufacturing requirements as defined in Zhang *et al.* [16]. Different possible manufacturing techniques were considered using the process models from Hermann and Thiede [4]. An example for these process chains is presented in Figure 4. It is important to note that this application case serve as a demonstration platform for the prototype software and is not claimed to yield an optimal process chain for the actual manufacture of such a device, as much more detail regarding specific product attributes would be required.

According to the criteria set in Figure 1, No. 2, the MM should be developed with appropriate MS. Alternative process chains have been developed with different MS dependent on the properties of the raw material. These are:

1) Milling on 2 separate billets on a 5-axes CNC milling machine, where the outer shape of the implant is roughed from both billets, followed by finishing. Once these two parts have been machined, they can be combined using a press fit between the holes on the one piece, and the pegs on the other piece.
2) A hybrid process chain using milling and SLM where the implant is divided into a top- and bottom section. The top section contains no complexities, which allows for easy machining. The bottom piece will be manufactured using the SLM process. All of the drug delivery channels are inside of the bottom piece.
3) The third process chain is using the SLM process to manufacture the entire implant, with emphasis on appropriate processing parameters.
4) For the fourth chain, a wire cutting and milling process are described. Two billets will again be used, but instead of using milling for the rough outer shape, wire cutting will be used on both billets. Finishing is performed on the milling machine.

The next step is to evaluate these chains according to user defined specifications in the evaluation hierarchy as per Figure 2. For this evaluation, the defined specifications are, Cost [South African Rand], manufacturing time [minutes] and material waste [kg]. If a part is to be manufactured for the purpose of making a profit, then the production costs are important. As soon as multiple parts are required before a given deadline, then the manufacturing time as well as the cost per part is of high importance. Titanium is an expensive material to purchase, and therefore a need exist to reduce the material waste for each step of the process. In

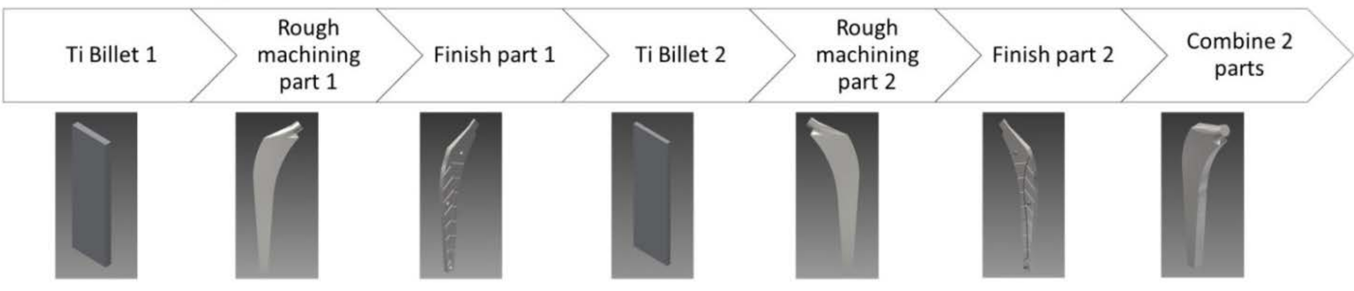

Figure 4 - Process Chain 1, milling on two separate billets

this case, the waste is defined as the loss of material during the manufacturing process in each MS. Furthermore, revenue from selling to recycling companies and ecological relief from use of recycled materials are not included in the scope. Specifications regarding the geometry, surface integrity and mechanical specifications should also be considered. However, such details considering the process chain in terms of manufacturing and also for intended use are outside the scope and purpose of this study. Furthermore, based on the needs of the user, details regarding evaluation criteria are bound to vary for different applications. To allow for user variability with regards to the identified focus areas in this paper, they were each evaluated at two levels, low and high. Since there are three focus areas, and weightings are required to total a hundred percent, the remaining two factors in the ratio has further been divided into two levels as well, yielding four combinations per factor. This is presented in Table 1.

Each MS involved in each process chain was entered into the program. For each process a value is required for the cost involved, the time of the process as well as the material waste, which was calculated as input material mass – output material mass. In order to evaluate the process chains against each other, the program requires upper and lower limits regarding each criterion.

	Low (Independent Static Variable)				High (Independent Static Variable)			
	#	C	T	W	#	C	T	W
Cost C [%]	1	20	26.6	53.4	3	60	13.3	26.7
	2	20	53.4	26.6	4	60	26.7	13.3
Time T [%]	5	26.6	20	53.4	7	13.3	60	26.7
	6	53.4	20	26.6	8	26.7	60	13.3
Waste W [%]	9	26.6	53.4	20	11	13.3	26.7	60
	10	53.4	26.6	20	12	26.7	13.3	60

Table 1 - Weighting set up for the simulation runs

This has been selected as the best and worst value for each criterion. For example, the best manufacturing time (for the entire process chain) will be the upper limit, and the worst time would be the lower limit. Each MS involved in each process chain was entered into the program.

Input values are based on current industry costs associated with each process, simulated manufacturing time and calculated material waste. A breakdown of the costs involved shows the hourly rate of each process, extra labour costs, tooling cost, programming cost, and material costs. The time factor is determined by calculating the time to complete each step in the process chain, and summing the time across the entire process chain.

For the evaluation it was assumed that one machine is available for a process step, and that no processes can be completed simultaneously. Material waste is defined as the difference in mass between starting material and final part design. Using the density of titanium, and volume information from the CAD software, the mass difference could be calculated. For the SLM processes, the mass of the support structure that is built by the SLM machine is the material waste for the process. The UserForm of the program requires input data for each process step of every process, for all defined evaluation criteria. The program was then executed for each of these combinations with the results summarised in Table 2. The stars behind the requirements in Table 2 imply that the requirement was an independent static variable at low or high specification. For each execution a graphical representation is printed to the user, an example is presented in Figure 5.

From Table 2, the CNC process chain (process chain 1) dominates especially when cost is of high importance and waste low. As expected, a process chain incorporating SLM becomes the best when waste becomes highly important. From this theoretical evaluation it is therefore evident that the program also reveals interactions between factors and their influence on the suggested process chain. For further evaluations of the program, more realistic manufacturing times should be utilised to allow for concurrent processes.

Setup Ratio #	Best Process chain	Low	High
1	Hybrid CNC-SLM	C*	W
2	CNC	C*	T
3	CNC	T	C*
4	CNC	W	C*
5	Hybrid CNC-SLM	T*	W
6	CNC	T*	C
7	CNC	C	T*
8	CNC	W	T*
9	CNC	W*	T
10	CNC	W*	C
11	Hybrid CNC-SLM	C	W*
12	Hybrid CNC-SLM	T	W*

Table 2 - Best process chain for different simulation runs in evaluation software

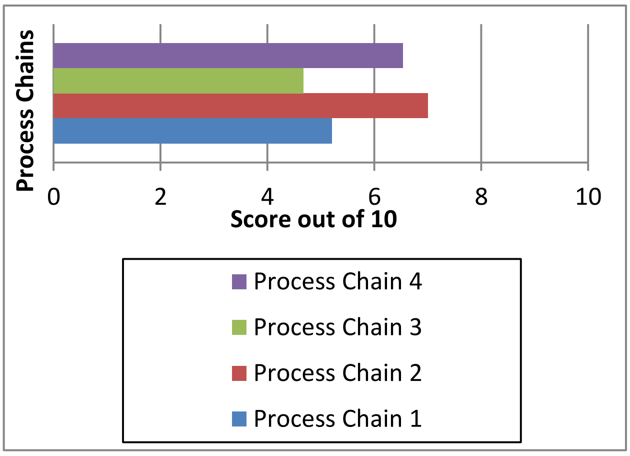

Figure 5 - Typical output for evaluated process chains from simulated weighting percentages

4 CONCLUSION

This prototype program proves to possibly be a helpful tool in evaluating process chains for a predefined set of specifications. If more detail is used within the set of criteria, a wider spectrum can be used to evaluate process chains. Therefore any criteria (if the input data is available) can be added, and the process chain can be evaluated accordingly. A benefit of this program is the fact that the evaluation of the process chain is done by evaluating each step separately. Therefore individual steps can be identified in order to specify where improvements can be implemented.

5 FURTHER WORK

At this point the *Guideline* and the *program* are not validated with an industry case study. Further work should therefore be to validate the program with examples from industry and eliminate bugs in the coding. The program can also be adapted to iteratively aid in improving processes with *Plan do Check Act* for obtaining more precise evaluations of a factory's production processes.

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7 BIOGRAPHY

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Modeling of Chip Curl in Orthogonal Turning using Spiral Galaxy Describing Function

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Abstract
With advances in modeling of machining process, a methodology for quantitative evaluation of the chip curl shape in orthogonal turning process is highly desired. To achieve this, a function to fit the varying chip curl was required. A mathematical function which is used to describe spiral galaxies is employed in this work which is able to accurately model wide variety of chip curl shapes. The function is employed to compare the chip curl predicted by numerical models with experimental investigations and it should be able to capture the variation of chip curl for varying cutting conditions ranging from tightly wound springs to comma shapes and the transition between them. This provides insights into the evaluation of cutting models from a practical view point. Finite element simulations were performed to predict the chip shape for varying tool rake angles and feed rates in orthogonal cutting process. The results show that the mathematical function was capable to model the wide variety of chip curl shapes encountered in orthogonal turning process. The chip curl predicted by the simulations show that numerical simulations need advanced models to depict work piece material behaviour, heat transfer behaviour and friction behaviour to predict the variation in chip curl shapes accurately for an orthogonal turning process.

Keywords
Chip curl, machining, finite element simulation

1 INTRODUCTION

Modeling of machining process has far reaching implications for its industrial relevance. With the advancement in scientific computing, various modeling approaches across different length scales have been employed to predict specific aspects of machining process and its outputs, finite element modeling has been employed in the modeling of chip formation process and significant progress has been made to the point of industrial applications [1][2].

Progress in modeling of chip formation in metal cutting has been well documented by two important key note papers within the CIRP community [3], [4] where in [3] the different scientific modeling methodologies from slip line field method to finite element method has been discussed. The more recent keynote paper [4] gives a detailed review of different methodologies and aspects of metal cutting like work piece material modeling, friction modeling and heat transfer modeling and their influence on industrially relevant parameters like chip morphology studies, residual stresses etc. are discussed.

A large amount of scientific work has focused on the force modeling aspects in metal cutting as it is an input for modeling of dynamic behavior of the cutting process, tool and machine tool [5]. With the advancement of numerical modeling of chip formation process and the lowering of computational cost, chip formation modeling is extended to other aspects which include residual stresses generated in the work piece during machining process and tool wear modeling.

One specific aspect of cutting process that is of importance from a cutting tool design view point is the modeling of chip curl. The curling of chip is attributed to the strain hardening, strain rate hardening and thermal softening behavior of the work piece material. Each of this aspect is related to the cutting process parameters like the cutting edge rounding, feed rate, cutting speed, chip breaker geometry, tool friction behavior and modeling of the cutting process. Orthogonal turning process is an important tool in the study of machining process to study fundamental relationships like cutting ratio, tool – chip contact length and shear angle. The chip curl in orthogonal turning process is studied to observe the work piece material behavior under the cutting conditions employed.

Fundamental work in the modeling of chip curl was carried out by several researchers [6]–[9] were chip curl in 2D and 3D is modeled using the parameters, chip back flow angle, chip up curl radius, chip side flow angle and chip side curl radius. In 2D cutting process, chip up curl radius and chip back flow angle can be used to model chip completely. In addition to the modeling of steady state parameters that are mentioned above, the prediction of chip curl variation due to contact of chip with the work piece in orthogonal turning process requires the modeling of chip curl for varying cutting length of cutting time.

Cook et al [6] modeled the variation of chip curl employing an exponential function where the variation of chip curl radius (r) from initial curl radius (r_0) is related by the following function

$$\frac{r}{r_0} = e^{n(\theta-\theta_0)} \tag{1}$$

The initial chip curl is modeled using a radius r_0 and the spiral component 'n' is a function of the chip rotation angle 'θ' and 'θ_0' represents the initial chip rotation. Chip rotation angle is a measure of the chip length in the polar coordinate. This work was extended by Stephen et al [10] where the modeling of chip curl in orthogonal turning process with chip breaker geometries is studied. The semi spiral chips are modeled using the following function

$$r = r_0 \left[1 + e^{\frac{\ln(1+\beta^{\theta-\theta_E})}{\ln(\beta)}}\right] \tag{2}$$

In equation 1, the value of θ for $\theta<\theta_0$ becomes zero and is termed the singularity property of equation 1. To avoid the singularity property and better control in the modeling of initial chip curl and chip curl variation a function developed by Ringermacher et al [11] is employed in this work.

In an earlier work [12], a methodology to assess the ability to use chip curl as a validation tool for evaluating FE simulation of chip formation and chip curl was carried out. The methodology utilizes computed tomography to obtain a 3D CAD model of the chip morphology. The chip 3D CAD model was used to evaluate the predicted chip curl models from 3D FE simulations in orthogonal turning process and is also extended to nose turning process. To utilize chip curl as an evaluation criteria in orthogonal turning process, the chip curl has to be measured for a statistically significant number of chips (10 – 30 chips) prior to the detailed examination of a few number of chips (2-3 chips). This calls for a measurement methodology more practical and rapid that could model the chip curl curve. In addition, the equations in literature require the initial chip curl radius as an input during modeling of the chip curl curve. This limits the ability for automated processing of the measurement methodology.

In this work, a methodology to evaluate chip curl geometry in chip formation simulation of orthogonal turning process is developed. Chip curl during orthogonal cutting process is modeled using a function that can fit shapes ranging from spirals to comma shapes. Experimental investigation utilized in the previous work [12] is utilized in this work as the process and the cutting parameters remain the same. Feed rate and rake angle are varied and chips of varying curl are obtained. The chip's curl is better modeled using the chosen function. Finite element simulation of chip formation process is carried out to evaluate its capability in predicting the chip curl geometry.

1.1 Spiral Galaxy describing Function

A function that could describe the change in chip curl radius (r) with varying input parameters like rake angle and feed rate in case of orthogonal cutting process is used. The function was initially developed to categorize spiral galaxies by Ringermacher et al [11] with three independent parameters A,B & N where A is a scaling factor (Equation 3). Parameter B and N control the spiral pitch. The radius is plotted in a polar plot with theta's range depending on the spiral length to be fit. In machining, the radius corresponds to the chip curl radius and theta is related to chip length.

$$r(\theta) = \frac{A}{\log\left[B \tan\frac{\theta}{2N}\right]} \tag{3}$$

The function falls in the category of non-Euclidean geometry of negatively curved spaces. It creates a bar initially and forms the curl which perfectly fits to simulate the variation of the chip's initial shape which is approximated to be a straight line when the radius is very large and the following chip curl curve. To fit the chip curl curve, the values of both B and N are to be optimized which increases complexity during parameter optimization. In addition, it is reported by [11] that the values could be degenerate which leads to different sets of B & N fitting the same curve. Hence a more robust function reported in the same work is utilized where the chip curl radius is modeled using one parameter called the angle of pitch at turn over and is as follows.

$$r(\theta) = \frac{R_\varphi}{1\text{-}\varphi_s \tan(\varphi_s) \log\left(\frac{\theta}{\varphi}\right)} \tag{4}$$

Using the above function (Equation 4), the value of φ is used to control the spiral of the curve and the value of R_φ(bar radius) controls the scale factor. This reduces the complexity during the optimization of the parameter φ_s(angle of pitch at turn over).

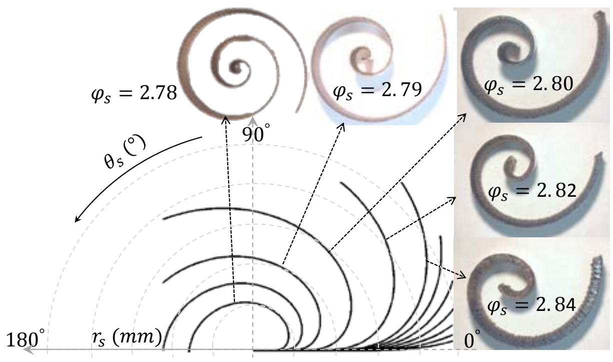

Figure 1 - Unwinding of the curve with increase in angle of pitch at turn over with the corresponding chip curl shape

By optimizing the values of φ_s in addition to the scale factor, R_φ, chip curl is described quantitatively. Figure 1 describes the unwinding of curve with increase in the value of φ_s and is able to characterize chip curl.

2 METHODOLOGY AND EXPERIMENTAL INVESTIGATION

This work is planned on the hypothesis that the chosen non Euclidean equation which is able to predict the shape of galaxies will be able to describe the variation of chip curl radius for varying feed rate and rake angle in orthogonal turning process of ferritic pearlitic steel. In addition, the variation of chip curl will be predicted by finite element simulation and the employed equation is used to evaluate its accuracy. Experimental investigation, finite element simulation and fitting of the chosen equation to the chip curl in two dimensions is carried out in this work.

2.1 Experimental investigation & finite element modeling:

The experimental investigation is summarized in this section, the details of which are present in the previous work [12] to the necessary detail. Orthogonal tube turning process is carried out in ferritic pearlitic steel, AISI 1045, with an average grain size of 13.5 µm and average hardness of 220 HV. The cutting parameters are chosen to reduce the tool wear to reduce the influence of variation of geometry change on the cutting process. A constant cutting speed is chosen with varying chip thickness and rake angle as shown in Table 1. The orthogonal turning process was simulated using finite element software specifically built for the simulation of machining process [13]. It employs an updated lagrangian model with adaptive remeshing strategies. 2D Simulations were performed as 2D chip curl geometry was the focus of study. The workpiece and tool geometry was modeled within the preprocessor owing to the simple geometry of both the tool and the workpiece.

Table 1 - Tool geometry, Workpiece geometry and process conditions.

Parameter	Values
Tool geometry	
Rake angle	:-5°;0°;5°;10°;20°;
Relief angle	:7°;
Edge radius	:30µm
Relief angle	:7°
Tool material	: H13A grade
Tool coating	: Ti-CN PVD coating
Workpiece geometry	
Workpiece diameter	: 146 mm
Chip uncut length	: 74.9 mm
Chip uncut thickness	: 3 mm
Process parameters	
Cutting speed (m/min)	: 150
Feed rate (mm/rev)	: 0.05;0.10;0.15;0.25;0.4;0.6

The work piece material's flow behavior is modeled using Johnson Cook model with the parameters obtained from literature [14]. The work piece - tool interface is modeled by temperature dependent thermal conductivity and heat transfer behavior of the workpiece material and a constant coloumb friction coefficient with the value of 0.5.

2.2 Methodology of fitting of function to chip curl in orthogonal turning process

With a mathematical function available to model the chip curl variation for varying cutting parameters, a methodology is required to fit the function to the experimentally obtained chip and numerically predicted chip curl. The methodology involves curve fitting to obtain the parameters of the function to describe the chip's curl. Curve fitting requires the function generated curve, the experimentally obtained chip curl's curve and an optimization technique to reduce the root mean square error between the two curves. To obtain the chip's curl, an image of the chip is used to obtain discrete points on the curve. These points are then used to describe the chip's curl. The function generated curve is obtained from a MATLAB function employing equation 2. In this work, Nelder mead method [15] is employed to calculate the error using the function generated curve as an error function. The challenge with this methodology is the value of φ is to be fine-tuned to 3 decimal points to perfectly fit the chip's curl curve. To improve the fitting of curves, the values obtained from the employed methodology are used in a graphic user interface to manually obtain the best fit. This could be avoided if more advanced optimization techniques could be used in the methodology.

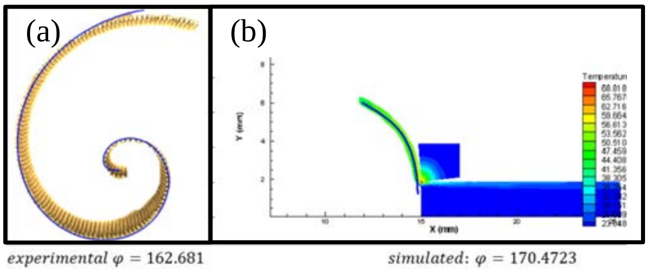

Figure 2 - Function generated curve (blue curve) fitted to experimental chip curl (a) and finite element simulation predicted chip curl (b).

As part of this work, the chip's curl is obtained by varying two cutting parameters, the rake angle and feed rate. Chip curl morphology is obtained when the orthogonal turning process is carried out by varying the rake angle at a constant feed rate of 0.15 mm/rev and by varying the feed rate at a constant rake angle of 5°. FE simulation predicted chip curl is obtained for the experimental conditions. The function is fitted to the chip curl predicted by FE simulation in a methodology similar to the one described for experimentally obtained chip curl. For fitting of FE simulation predicted chip's curl with the function generated curve, the function's parameters are obtained directly using the GUI based program Figure 2.

3 RESULTS

With the main aim of this work to define a methodology for quantitatively describing the chip up curl geometry in orthogonal turning process, experimental investigation and finite element simulations were carried out as described in the previous sections. The variation of chip up curl geometry for variation of rake angle and feed rate is plotted in Figure 3. In addition, figure 4 shows the cutting force variation for variation of rake angle and feed rate.

A small chip curl factor φ_s dicates the chip to be more curled and a larger chip curl factor indicates the chip to be less curled. With increase in rake angle, the chip is observed to become more curled in the experimental investigation and this variation of chip up curl geometry is predicted by the finite element simulation model employed. In addition to the variation of chip curl, the cutting forces between experimental investigation and simulation is plotted and it is observed that a similar trend as chip curl is observed.

Similarly the variation of chip curl with variation in feed rate is plotted. It is observed that with the increase in feed rate, the chip is less curled. The decrease in curling of the chip is shown by the increase of chip curl factor φ. The finite element simulation of chip curl is not able to predict this variation of the chip curl observed during experimental investigation. In addition, the plotting of the cutting force variation with the increase in feed rate shows the trend to be similar to chip curl variation in orthogonal turning process.

4 ANALYSIS

The fitting of the chip's up curl geometry obtained from 2D orthogonal turning process by the chosen mathematical function shows the mathematical function's ability to model the chip's up curl variation for varying cutting process parameters. The function's parameter, φ_s is able to predict the different chip up curl geometries.

Figure 3 (a) and figure 4(a) shows that the chip up curl geometry variation with varying tool rake angles and constant cutting parameters have a very similar trend to the cutting force variation (figure 4 (a)) in

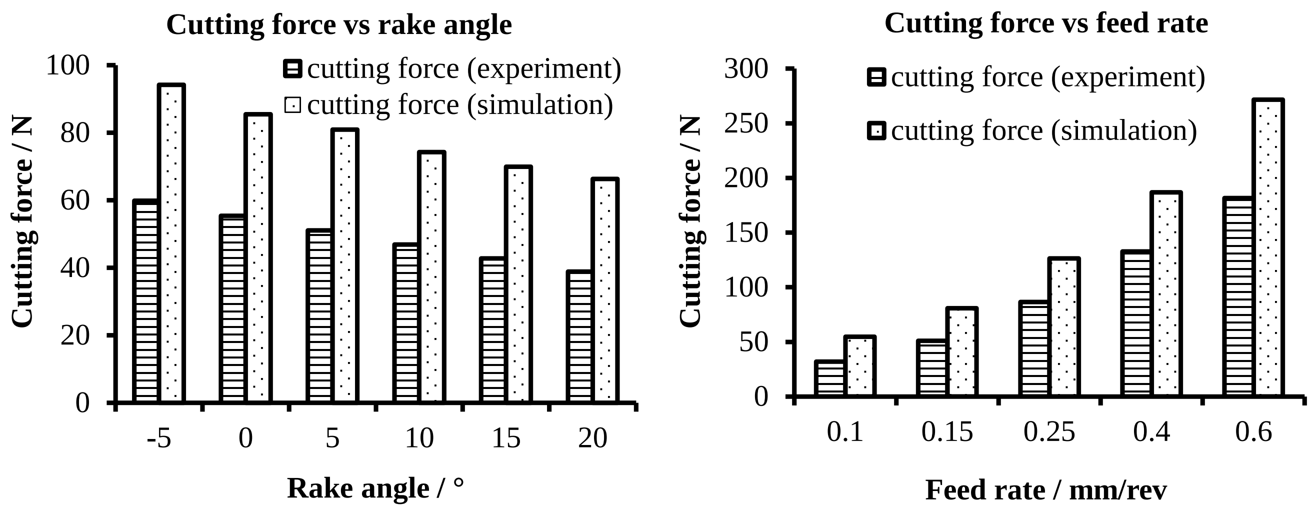

Figure 3 - Variation of cutting force for variation of rake angle at constant feed rate 0.15 mm/rev and variation of feed rate at constant rake angle of 5°.

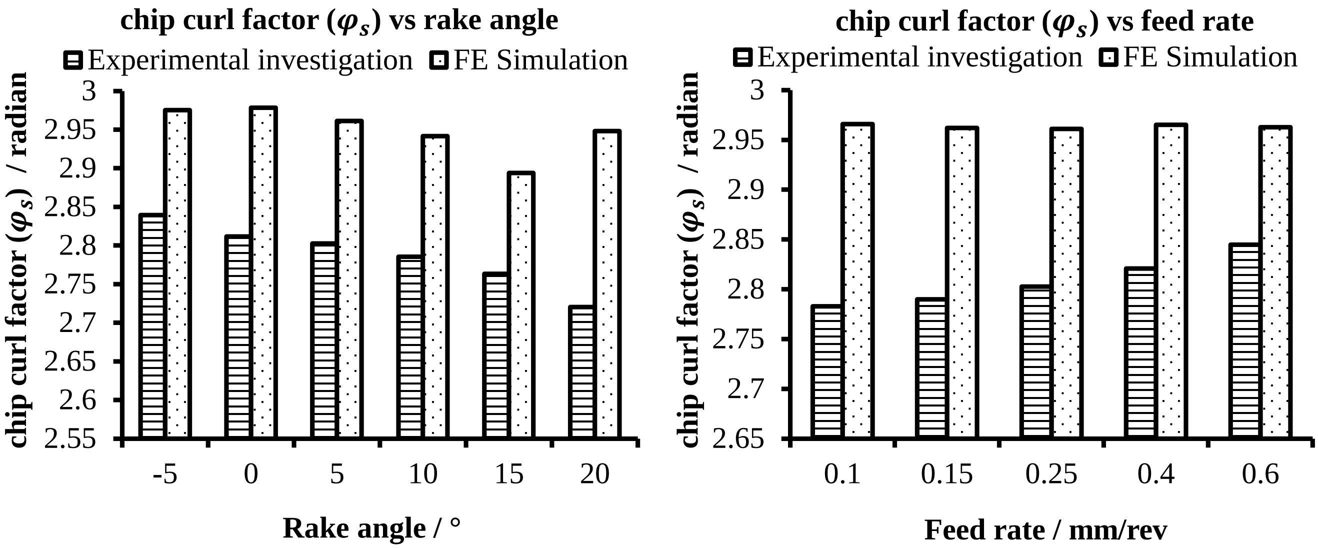

Figure 4 - Variation of chip curl factor (φ_s) for variation of rake angle at constant feed rate 0.15 mm/rev and variation of feed rate at constant rake angle of 5°.

both experimental investigation and finite element simulation. With the trend being predicted by the finite element simulation, the quantitative prediction of chip curl parameter is poor and needs improvement. The difference in absolute values between the cutting forces obtained from experimental investigation and predicted finite element forces also show the need to improve the finite element models used. The change in chip curl factor in FE simulation at a rake angle of 20° can be attributed to a short tool chip contact length.

Figure 3(b) and Figure 4(b) shows the variation of chip curl factor φ_s and cutting forces for varying feed rate with all other cutting parameters being constant and the tool geometry being constant. With the increase in feed rate, the cutting forces increase owing to the increase in uncut chip thickness and is well documented. The chip up curl geometry variation with the increase in feed rate obtained from experimental investigation shows that the chip is less curled with the increase in feed rate. This variation is less predicted by the finite element simulation predictions. This could be strongly attributed to the influence of adiabatic shear and segmented chip formation in metal cutting. With the variation of tool macro geometry under constant cutting parameters, the variation of cutting process from continuous chip to segmented chip is less pronounced whereas the variation of feed rate from 0.1 mm /rev to 0.6 mm/ rev shows change of cutting process from a continuous chip to segmented chip. This variation of cutting process leads to more unwinding of the chip compared to tool macro geometry variation. This is shown by the variation of cutting process chip curl factor from 2.7 to 2.8 for variation in tool rake angle and chip curl factor variation from 2.7 to 3 for variation in feed rate. The finite element simulation predictions show that the variation of chip curl for variation in tool rake angle in particular and tool macro geometry is very well predicted whereas the variation of chip up curl for variation in feed rate is not predicted. This could be attributed to the work piece material modeling employed in this work. The Johnson Cook model which is used to predict the work piece material's flow behavior is not capable to predict the formation of adiabatic shear bands which in turn results in chip segmentation. With the chip segmentation being more pronounced with the variation of cutting process parameters employing a constant tool geometry compared to variation of tool geometry employing constant cutting process parameters, the variation in chip curl could not be predicted by the finite element model.

5 CONCLUSION

In this work, a practical methodology to quantitatively characterize chip up curl geometry in orthogonal turning process is developed. The chip up curl geometry is obtained from experimental investigations and finite element simulation of chip formation process is carried out. A mathematical function which is employed to characterize the spiral galaxy shape is employed and is found to be able to predict the chip up curl geometry variation for varying cutting process parameters and cutting tool macro geometry obtained from experimental investigation. The variation of chip up curl geometry is successfully modeled using the employed mathematical function. The finite element simulation is able to qualitatively predict the variation of cutting forces for both variations of tool geometry and process parameters although the quantitative prediction needs to be improved for employing finite element simulation in cutting tool macro geometry design. In addition, the finite element simulation's ability to predict the variation of chip shape from continuous to segmented chip formation is critical to predict the variation of chip curl for variation in cutting process parameters and are to be employed in addition to work piece flow curve modeling.

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Low Level Task Execution, Programing and Control for Jigs, Fixtures and Equipment

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Abstract
Current manufacturing technologies are unable to facilitate customer demands in creating unique, customized products. The Factories of the Future initiative aims to address this problem through the development of software, control systems and hardware that can facilitate customization in a manufacturing system, at reasonable cost and in an acceptable time frame. Eliminating unwanted conditions such as chatter, through selecting and adjusting machining parameters, is of importance for cost and time effectiveness.

This paper focuses on investigating whether fixtures are capable of providing active support, in the minimisation of chatter, during machining operations for advanced manufacturing systems. The reconfigurable fixture used as a platform for this research is reviewed. The causes of chatter are analysed and simulations on the natural vibrations of a machined part are conducted. It is found that there is a relationship between material removal and the natural vibrations of the part, providing opportunity for further testing.

Keywords
Fixtures, Vibration, Chatter

1 INTRODUCTION

Current machining in today's market is extremely competitive. By eliminating limiting conditions such as chatter through the integration of intelligent fixture systems into manufacturing processes, substantial saving in machining costs can be achieved because chatter is the most problematic and limiting factor of machining [1].

The present efforts in minimizing chatter during machining have focused on making machine tool structures more rigid, re-engineering cutting tools, redesigning spindles and other such endeavours, but not much attention has been paid to how the work holding part of a machining system influences chatter [2]. According to Kennametal Engineering it is possible to reduce vibration and chatter simply by reworking the fixture to hold the work piece more securely [3].

The Factories of the future initiative aims to develop the manufacturing technologies necessary to allow customers to order a customized product at an affordable price and have it delivered in a reasonable time frame. It is expedient for such a manufacturing system to make use of intelligent, reconfigurable jigs and fixtures to accommodate the increased variety of part types and geometries.

The optimization of such fixtures is of the utmost import as work-holding is a major factor in the context of both individual machining system performance and overall process performance [2], with around 40% of parts rejected in machining being connected to poor fixture design [4]. Furthermore the reduction of rework on part fixturing can lower the time and cost of the manufacturing process [5]. Reconfigurable fixtures provide a platform for the investigation of fixturing as a source of chatter reduction.

This research determined to introduce a level of intelligence to a proposed Automated Flexible Fixture (AFF) by investigating whether said fixture was capable of providing active support, in the minimisation of chatter, during machining operations. The research method conducted consisted of simulating the vibrational harmonics of a workpiece undergoing a series of material removal processes. This was to be followed by simulations of the workpieces response to different clamping scenarios. The final aspects of the research were to be future physical testing to validate the simulation results and to develop a basic control concept for intelligent chatter control.

2 FIXTURE INTELLIGENCE

The intelligence desired for the AFF is that of machine learning. The fixture should, over time, have the ability to optimize the fixturing of a specific work piece so that the vibration of the system is within a certain limit. Ideally that limit should be the point just before chatter occurs. The AFF will then store the knowledge gained by that machining operation for use in optimizing similar fixturing problems.

Before such a control system can be developed, research into the relationships between vibrations caused during machining and fixturing must be conducted.

3 THE PROPOSED FIXTURING SYSTEM

An automated flexible fixturing system was designed by Graduate student Andrew Ilidge with the purpose of facilitating the increase of part variety in a manufacturing system. The flexible fixture has the ability to reconfigure itself to accommodate new parts in a manufacturing process, and multiple fixturing scenarios.

Figure 1 shows the complete fixturing system designed. Its basic components were the fixture bed, seen in the centre, and the clamping pins positioned on opposite sides of the fixture bed. The clamping pins each attached to 3 lead-screw runners that gave them their 3-degrees of motion. The pins were able to move inwards towards the fixture bed, which will be referred to as the z-direction. They also had the ability to move horizontally in the x-direction, and vertically in the y-direction.

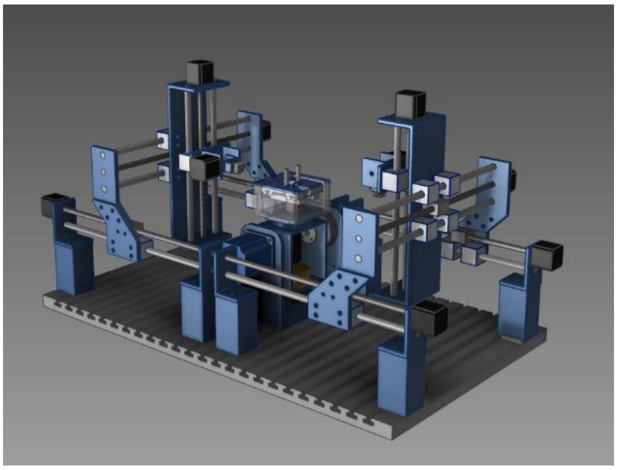

Figure 1 - Complete fixture assembly [6]

3.1 Fixture components

3.1.1 Fixture bed

The fixture bed, depicted below in Figure 2, had the primary purpose of locating the work piece onto the fixture. It achieved this through two locator pins that gripped each new part through matching holes in the part. This feature will be used in the future to facilitate the automation of loading a work piece onto the fixture.

Illustrated in Figure 2 are locator pins and the base assembly that made up the fixture bed. The base assembly consisted of two actuators that gave the locator pins two rotational degrees of freedom.

The locating pins of the fixture bed were not designed to hold the work piece against cutting forces.

Figure 2 - Fixture bed assembly [6]

3.1.2 Fixtures clamping pins

The fixtures clamping pins were designed to mould around any contoured workpiece geometries and lock in place. It achieveed this through a pin field, depicted in Figure 3, where each pin could move freely and independantly, and were locked in position using a servo mechanism that moved a locking plate into place. Furthermore each of the two clamping pins had 1 degree of rotational freedom about the horizontal-pin that mounted them to their lead-screw runners.

4 VIBRATION AND CHATTER

In order to determine how best to investigate the relationship between vibration,chatter and fixturing, a clear understanding of chatter and its causes was necessary. The literature that follows outlines the types of vibrations that exist in machining.

4.1 Types of vibration

Chatter is a self-exciting vibration that can occur during machining operations and is a common limitation to productivity and part quality [1]. Chatter is not the only unwanted vibration in a system, there are 3 main types of vibration in a machining system: Free, forced and self-excited vibration.

- Free vibration is the frequency that a body will naturally tend to vibrate at when acted apon by an excitational force, for example the vibration of a guitar string after being plucked [1]. It is also known as the harmonic or natural frequency of the system. Each system has multiple frequencies that it tends to vibrate at, which are dependant on the excitational force These are known as the harmonics of the system and correspond to the number of modes of vibration at each natural frequency [1].
- Applying a periodic force to a system causes forced vibrations [1]. Such periodic forces may be caused by an imbalance in a machine tool, or simply the cutting forces from the milling cutters

[1]. When forced vibrations occur at a period or frequency that equals one of the harmonic frequencies of the system, it causes excessive vibration known as resonance.

- Self-exciting vibration, also known as chatter, is caused as each new cut of the cutting tool rebounds off of the previous tooths' cut, in a feedback process, that causes waviness on the cut surface [1]. This happens when the chip width exceeds a limiting value that depends on the dynamics of the machine setup [1]

5 ASSUMPTIONS AND CONSTRAINTS OF RESEARCH

As this research area was broad in scope, it was necessary to set suitable constraints in place in order to achieve a tractable problem space.The following sections outline the contraints and boundaries that were chosen for this research.

5.1 Workpiece

5.1.1 Workpiece size

The work piece size was constrained by the ability of the AFF to accommodate it spatially. The AFF was designed to fit within a Computer Numerical Control (CNC) router, to accommodate testing machining operations.

The first constraint to the work piece was the locator pins on the fixture bed. The minimum distance achievable between the pins is 43mm centre to centre, with the pins being 5mm in diameter.

The Movement of the clamping pins are:

- 150 mm veritcal movement (y-direction) from fixture bed upwards
- 180 mm Horizontal movement (x-dirextion) to either side of the fixture bed
- 350 mm maximum distance between pins in z-direction

The locator pin fields consisted of a 5x5 matix of pins each 4.5mm in diameter (see figure 3), that filled a square area with 30 mm side lengths. it was desirable that the full pin field be in contact with the workpiece surface and therefore this became the minimum constraint.

Thus the maximum work piece dimensions were 150mmx180mmx350mm and the minimum side clamping area was 30mm squared.

5.1.2 Workpiece geometry

For the sake of simplicity the work piece geometry was chosen as a rectangular cube. This geometry will be advantages as it will minimize the material wastage during the preperation of workpieces for non-destrucive testing and during machining for destructive testing. This geometry was also chosen in order to simplify the options for clamping the workpiece.

5.2 Degrees of freedom

5.2.1 Machining operations

It was noted that while conducting simulations any type of workpiece geometry could be drawn in Computor Aided Drawing (CAD) software, that may not necessarily be achivable through the machining techniques available to the researcher. This will an important consideration for future simulations and testing.

5.2.2 Clamping scenarios

The 10 degrees of freedom made the fixturing possiblities for any workpiece nearly limitless. This research focused on clamping scenarios where:

- There was no tilt or rotation of the fixture bed assembly about either of its 2 axis
- There was no rotation of the clamping pins
- The clamping pins clamped the workpiece directly oposite to each other

6 MATERIAL CHOICE AND CHATTER

6.1 Material properties

When physical testing takes place there will be a need to select the workpiece material. In order to choose a material for simulations it was necessary to know how that materials properties would effect the way it responds to machining, so that the simulations would translate effectively into physical testing. This section attempts to define how a material properties will effect its potential for chatter.

The following sections address the different possible material types and properties.

6.1.1 Youngs modulus

Youngs modulus is a material property that indicates a materials resistance to changes in length [7] or its stiffness. Because vibration is related to changes in the length or shape of a material, a stiffer material will vibrate with a smaller amplitude which corresponds to a higher frequency.

6.1.2 Ductile materials

Two material cases, namely type 2 and type 3 copper alloys, were investigated to determine the effect that ductility has on machinability.

When type 2 copper alloys are machined, the cutting tool tends to shear the chips off laterally in a series of closely spaced steps that raise the potential for chatter [8].

The machinability of type 3 copper alloys can be related to the fact that this softer material tends to deflect under the pressure of the cutting tool, which reduces dimensional accuracy and can increase the risk of chatter [8].

Thus it would appear that ductile materials are more prone to chatter at a lower frequency due to self-exciting vibrations then at a higher harmonic frequency.

6.1.3 Stiff materials

Aluminium alloys tend to be high in stiffness. One such alloy is Aluminium silicon carbide mica. This alloy offers high dampening ratios when compared to its base metal of aluminium [9]. Such alloys may be suitable for testing vibrational response for high speed machining.

7 VIBRATION SIMULATIONS

The purpose of the simulations conducted was to investigate the effect of material removal during machining operations on the vibrational properties of the workpiece.

Further simulations are currently being conducted on the vibrational characteristics of a workpiece for different fixturing scenarios.

7.1 Parts

The Figure 4 shows a cubic wokpiece at different stages of material removal. The workpiece stages are denoted (a) through (f) in Figure 4, and are labelled in the tables and graph as part 1 through part 6 respectfully.

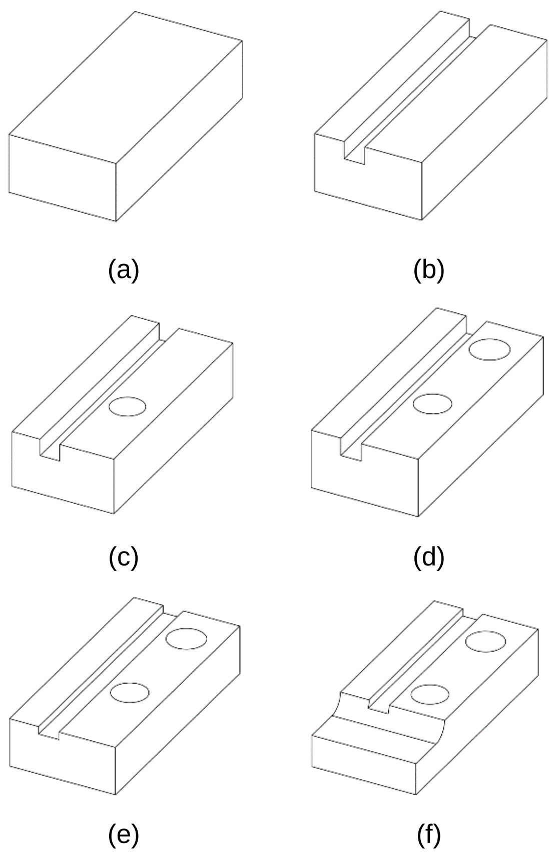

Figure 3 - Part geometries

Part 1 is a rectangular cube of dimensions 30mmx50mmx120mm. In part 2 a slot was cut along the length of the workpiece. A hole was then drilled through the thickness of part 3, after which another hole was bored halve way into the workpiece seen in figure 3 (d). The removal of the top surface layer is shown in Figure 3 (e) for part 5. Finally part 6 was created by removing the top front surface with a filleted edge.

7.2 Simulation

The simulations were perfomed using the SolidWorks Vibration Simulation package. The simulations purpose was of a qualitative nature, to determine the effect of material removal on the vibrational harmonics of a workpiece.

7.2.1 Fixturing choice

The rear facing surface of each part was constrained to be fixed during the simulations.Part 4 is illustrated in Figure 5 showing the rear facing surface constraint.

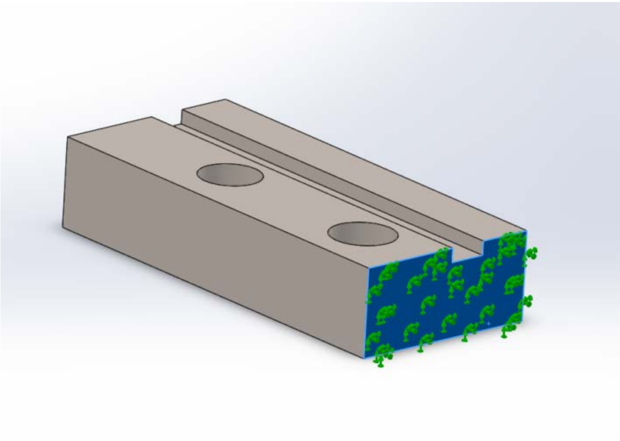

Figure 4 - Fixed geometry for part 5

7.2.2 Material

The material chosen for the simulation was Aluminim alloy 1060.

Harmonic Frequencies	Part 1 (Hz)	Part 2 (Hz)	Part 3 (Hz)	Part 4 (Hz)	Part 5 (Hz)	Part 6 (Hz)
1st	2043	1999	1888	1946	1642	1104
2nd	3357	3336	3181	3267	3282	2890
3rd	6643	5873	5518	5560	5416	4570
4th	10342	10179	9934	9854	8801	7757
5th	13147	12944	11874	12051	12142	11239

Table 1 - Table of harmonic frequency simulation results

7.3 Results

The simulations yielded the first 5 harmonic frequencies, in hertz, of each part. These results are found in Table 1.

A graph of the first harmonic frequency of each part was plotted in Figure 6. The trend observed was that as material was removed from the workpiece the harmonic vibrations decreased. This trend held true for all 5 of the harmonic modes. There was also the unique case of part 4 where the boring of the hole produced an increase in vibration response instead of a decrease. This occured across 4 of the 5 harmonic frequency results.

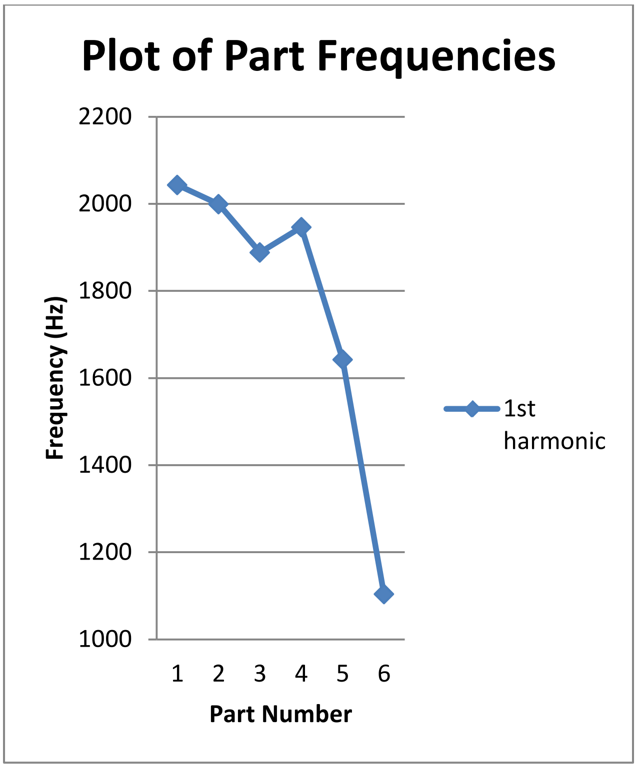

Figure 1 - Graph of first harmonics

8 DISCUSSION

The purpose of the simulations was to determine if there were any trends to the vibrational response of a workpiece that undergoes material removal. Any trends that emerged were to be used to predict if there was an opportunity for fixturing to play a role in vibration reduction.

These simulations were to be used as a premise for the use of fixturing as a means of chatter reduction, scince it was not possible to simulate chatter on a computor model. The physical testing of the theories developed from the vibration simulations would then be used to prove wether chatter reduction was possible, within the constraints that were set for the research, and develop a control theory around the emphirical results.

Such a chatter control system could be implemented in several ways. It could be used in operations where a certain cutting speed was desired in order to achive a quality surface finish on the product. If chatter occured intermittently during machining, changing the fixturing scenario might be the alternative to changing the cutting conditions. This is the type of outcome this research desired to achieve. How the fixturing scenario must change to reduce chatter will be investigated in future work.

From the results contained in Table 1 it can be deduced that a workpiece fixtured in a single scenario for a series of machining operations put it at risk of high vibrational feedback. This was because the harmonic vibrations decreased during the machining operations, which is an indication of the workpiece losing rigidity, which increases the risk of chatter. This suggests that by changing the fixturing we might find a more efficient fixturing set-up by reworking the fixturing to increase rigidity in areas that have lost rigidity.

This singularity that occurred in part 4 may be a repeatable physical phenomen that is a functiuon of the holes positioning on the workpiece, or it could simply be an anomaly in the simulation due to the part geometry. Future investigation into wether this is a repeatable phenomenon will be conducted.

9 FUTURE WORK

Future work will employ physical testing to validate the simulation results. This testing will consist of both the non-destructive and destructive testing of the workpiece, to characterise the chatter environment. Non-destructive testing will be used to determine the workpieces harmonic vibration frequencies for different clamping scenarios. Destructive testing will be used to compare different fixturing scenarios effectiveness during machining operations.

10 CONCLUSION

In conclusion, it has been found from the research that work holding is able to improve work piece rigidity by adapting to the change in harmonic vibrations. The results obtained validate the possibility that workholding can actively reduce the negative effects of chatter in machining operations, in order to facilitate customization in a manufacturing system. Validation through this research and future work will further enhance these results.

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12 BIOGRAPHY

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The Design and Manufacturing Considerations of a Paper-Based E. coli Biosensor

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Abstract

Printed electronics employs additive manufacturing processes and has several application possibilities. One such possibility is a low-resourced point-of-need market which is the intended use of a proposed paper-based E. coli (Escherichia coli) biosensor. This aligns with the ASSURED (affordable, sensitive, specific, user friendly, robust and rapid, equipment free and deliverable) guidelines of the World Health Organisation (WHO) for diagnostic tools. This biosensor is presented with the main focus being the refinement of the manufacturing process. The ink-jet printed biosensor is printed onto a paper substrate using silver ink. The design, simulations and several manufacturing considerations of the biosensors are described. When considering a digital factory mind-map, this paper-based E. coli biosensor is still in its product development phase. However, by refining the manufacturing processes printed electronics allows for rapid-prototyping and effortlessly implementing design changes that accelerate the design process as well as accelerating large scale manufacturing in the future.

Keywords

Printed electronics, biosensor, E. coli

1 INTRODUCTION

It is well known that some strains of E. coli (Escherichia coli) are dangerous to human health. These strains of E. coli cause kidney failure, anaemia and severe diarrhoea. Furthermore, the presence of E. coli in a water sample is also an indication that other harmful microbes, such as salmonella and listeria, could be present in the contaminated water [1].

Biosensors have a wide range of applications with the added advantage of offering a low manufacturing cost. Therefore, biosensors are ideal due to their economic feasibility for monitoring water contaminants in rural regions. Various methods of biosensing exist, including surface plasmon resonance (SPR), acoustic wave-based biosensing, aerometric sensing, potentiometric biosensing, microelectrode array biosensing and capacitive sensing [2-4]. A capacitive biosensor measures the permittivity of an analyte used as the dielectric of a parallel plate capacitor. Capacitive biosensors have low detection limits and may be used to measure antigen, antibodies and E. coli [5]. Microelectrode arrays such as interdigitated electrodes (IDE's) can be used to measure a capacitive difference between two of these IDE pairs to identify E. coli in an analyte [6]. Often the IDE's are manufactured using printed circuit boards, which are very expensive and have a long manufacturing time in comparison to a paper substrate [7].

The manufactured E. coli biosensor helps the development of ASSURED (affordable, sensitive, specific, user friendly, robust and rapid, equipment free and deliverable) guidelines for diagnostic tools. The developed paper-based biosensor presented in this work is manufactured using interdigitated electrodes. This is an effective approach to generate a large capacitive value in a small space, since the branches can be located close to each other and these form part of two parallel plate capacitors. In this paper the design considerations, simulations and manufacturing of the biosensors are described. It is found that there are several manufacturing considerations that play a role, including conversion differences between different software layout formats, the physical printing parameters, the properties of the ink that influence the minimum feature size, as well as thermal curing challenges due to different material temperature coefficient of expansion (TCE) rates. From the above mentioned design and manufacturing considerations, the parameters allowed for the IDE pairs to be successfully manufactured are identified and discussed.

2 OPERATING PRINCIPLES OF THE BIOSENSOR

A factor that has to be taken into consideration when implementing a parallel plate capacitor, is that a parallel plate capacitor has finite dimensions which generate fringing capacitance. The discontinuity of the material creates a radial component in the electrical field which generates parasitic capacitive components on the sidewalls of the capacitor [8]. Parasitic capacitances that are present in microsensors have a significant influence on the capacitive measurement of the parallel plate capacitor and also on the measured permittivity of the analyte. A modified analytical model is used to approximate the influence of the parasitic fringing capacitance of the electrode configuration. This is necessary to minimise the errors that occur during the capacitive difference measurements between the two IDE pairs. The first electrode pair serves as a reference electrode where non-contaminated water is used as the dielectric medium. The second electrode is covered by an antibody coating to which the E. coli cells present in the analyte will bind. This second electrode then forms the measurement electrode, with the dielectric consisting of a mixture of water and E. coli. Figure 1 shows a concept design of a proposed IDE pair, where the minimum feature size of the design is 50 µm. The relevant design dimensions are also illustrated, with L_{total} the total length of the electrode pair and W_{main} the width of the parallel plate capacitors where the largest capacitance is generated. W_{total} is the total width of a single electrode.

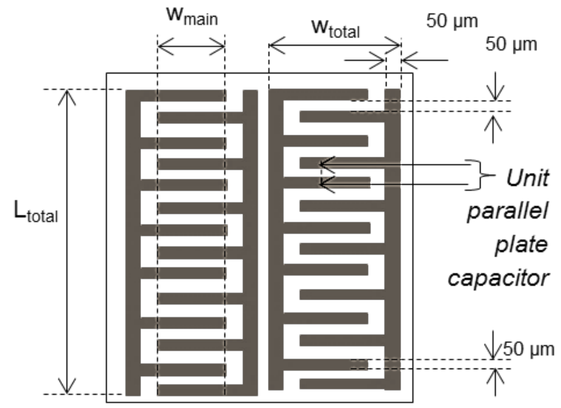

Figure 1 - The concept design of a proposed IDE electrode pairs.

The E. coli measurement will essentially be based on the change in this dielectric constant resulting from the difference in permittivity of E. coli compared to water. However, all the elements present within the measurement setup, including water, the antibody and E. coli, also have resistive properties that should be taken into account. Figure 2 shows an illustration of an equivalent electronic circuit for an E. coli cell in the dielectric space of an electrode. This IDE was manufactured on a silicon substrate [3].

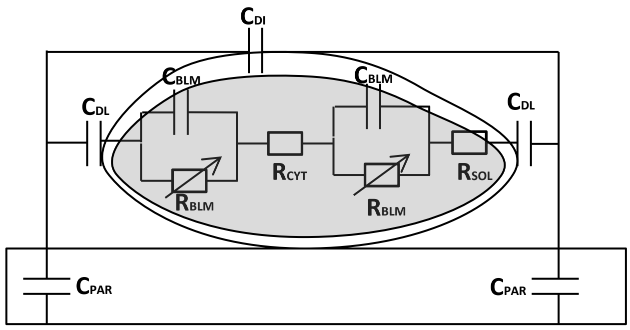

Figure 2 - Equivalent impedance measurement circuits with E. coli present in an analyte [3].

C_{DI} is the capacitance created due to water, C_{DL} is the double layer capacitance which exists at lower frequencies due to electrochemical effects. C_{BLM} and R_{BLM} are the respective capacitances and resistances of the E. coli cell wall and R_{cyt} is the resistance of the cytoplasm. Figure 2 also illustrates several high impedance values (low capacitive values) in series with several low impedance values (resistive values). If low resistive values are in series with small capacitive values, it will amount to the impedance being equivalent to that of the capacitive values, equating to only the Cdl, Cdi and Cblm values.

Capacitors in parallel accumulate, therefore the higher the concentration of E. coli colony-forming units (CFUs) per millilitre in the analyte, the more significant the capacitive value of the E. coli between the electrode branches will be. By considering that the E. coli will attach to an antibody, it is conceivable that the E. coli cells can be concentrated at a certain point. Therefore, the measurement electrode is coated with the antibody, resulting in an accumulation of E. coli within the measurement region and creating a differential impedance compared to the reference electrode. The greater the number of IDEs in parallel, the higher the difference between the two IDE pairs. By recording this difference the concentration of E. coli in a sample can be identified.

3 MANUFACTURING PROCESS

The following section describes various development and manufacturing considerations and challenges encountered during the initial prototyping of the first working sensors.

3.1 Manufacturing equipment

The biosensor is printed using the Fujifilm Dimatix DMP-2831 drop-on-demand piezo inkjet printer. The Dimatix printer allows for multilayer printing and has a mechanical resolution of 5 µm. The cartridge used with the Dimatix printer is the DMCLCP-11610 Dimatix Materials Cartridge. A cartridge has a minimum drop volume of 10 pl as well as 16 nozzles, each having a 21 µm orifice. The minimum printing feature size is not only dependent on the drop volume and the orifice size, but also on the drop spreading (due to the substrate properties) and drop angle. Epson Premium glossy photo paper was used for this work. This paper is the recommended paper for the Dimatix printer, and has a hydrophobic resin-coated surface that is ideal to use in paper-based printed electronics [9].

Harima NPS-J nano silver ink-jet printable paste (Harima Chemicals Group Inc, Japan) was used to ink-jet print the biosensors. This NPS-J ink consists. The physical properties of the Harima NPS-J ink include: a silver concentration of 56.8 wt%, a viscosity of 8.4 mPa.s, a density of 1.81g/ml.

The sensor designs consist of different numbers of IDE branches for characterisation purposes. After these design were identified, the sensor printing commenced. The silver ink freezes at a melting temperature 4.5˚ C. Therefore the fridge should be kept between 4.5 - 8˚ C. The silver ink should not be injected into the cartridge immediately after being removed from the fridge. Gently stir the ink, using an Ultrasonicator, and thereafter leaving it in an open environment, for approximately an hour, to slowly reach room temperature will suffice.

3.2 Software based Conversion

The ACE 3000 V7 is used to convert the design files into a specialised bitmap picture file (bmp. file) that takes drop spacing and line width into account as illustrated in Figure 3.

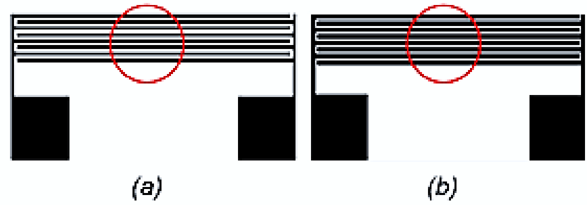

Figure 3 - Drop spacing differences causing a (a) correctly converted bitmap image and an (b) incorrectly converted bitmap image.

There are three possible solutions to the problem illustrated in Figure 3. The first is to decrease the nozzle voltage or change the waveform in order to decrease the drop size. This solution does not decrease the drop size significantly enough and can cause the nozzles to block. The second solution is to change the design in order to compensate for the non-zero line widths and drop spacing dependant conversion. The proposed IDE consists of several branches therefore if one branch does not coincide with the drop spacing layout, the conversion will be incorrect and the design will have to be redesigned. This is therefore also not an optimal solution, because this complicates the design phase. The third solution is to optimise the drop spacing selection. When selecting a drop spacing which is not factor of the minimum feature size the branch widths increase and overlap in the y- axis. When selecting the drop spacing too small (5 um drop size for a 50 um minimum feature size), it causes too many drops to dispense creating a blob which leads to the ink overflowing on the paper. When a drop spacing is selected that equals the minimum feature size of the design and the feature size is bigger than the drop size (between 30 and 35 um), it generates open spaces in the x-axis as illustrated in figure 4.

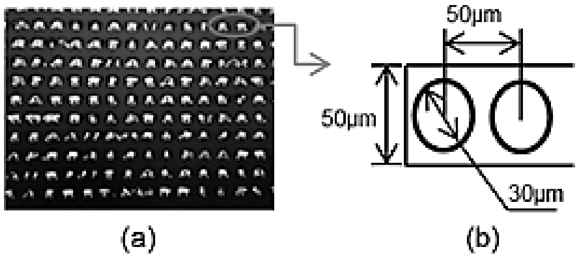

Figure 4 - An image and explanation of printed branched using 50 µm drop spacing.

When selecting a drop spacing which is a factor, but not equal to, of the minimum feature size the conversion is done correctly. A 25 um drop spacing was selected which caused two drop to print per line, generating a line width between 50 um and 55 um. This lead to the drops still overlapping that decreased the possibility of the generation of an open circuit when the sensor is printed. Furthermore, when converting the design file, select to convert the extent of the design not the display. This is done to eliminate white spaces that cause alignment problems when multilayer printing.

In summary, the drop spacing that is selected to convert the design file to a bitmap file should be a factor (larger than 1) of the minimum feature size of the design and the extent option should be selected, not the display option.

3.3 Printing refinement

There are various factors to take into account when printing due to the fact that every cartridge reacts differently. These include platen temperature, nozzle temperature, jetting voltage, meniscus strength and waveform. Each of these settings has an influence on either the drop size or viscosity or both. By increasing the nozzle temperature the viscosity of the ink is lowered. This causes the drop size to decrease and the drop dispensing to appear to accelerate. The jetting voltage and waveform also influences the drop size of the printer. By increasing the jetting voltage, the drop size is increased, however, it was found that depending on the ink, this does not always result in a significant change. Should the ink be more viscous, causing the drop forming to fail, an increase in voltage can help to overcome this. The drop size varies with waveform. Increasing the ON duration of the waveform results in a larger drop and vice versa [10]. It was observed that the waveform has the largest influence on the drop size. By using the incorrect combination of the slew rate and drop ON duration (such as a 0.1 us slew rate and a 14.8 us ON duration) drops can also seize to form. In order to avoid this, small changes to the waveform must be made at a time. Various cleaning cycles can also be compiled. A cleaning cycle consists of a spit, purge and blot function. By increasing the spitting and purging time the some clogged nozzles can unclog. The platen temperature appears to have an influence on the adhesion of the silver ink to the paper substrate. It was found that to set platen temperature equal or larger than the nozzle temperature helped with adhesion and drop formation during the printing cycle. Figure 6 - Figure 8 shows such instances where the wrong combinations of the above mentioned settings lead to incorrect results.

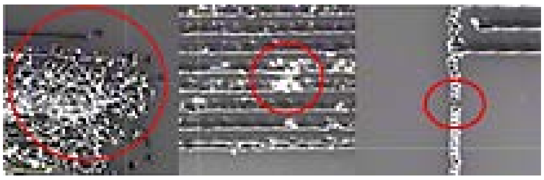

Figure 5 - (a) A misformed printed IDE generated because of uncharacterised cartridge settings, (b) A short circuit formed because of drop misbehaviour rendering the IDE pair useless and (c) An open circuit in printed sensor due to gaps in the printed vertical line.

The results shown in Figure 5 (a) was generated either by viscosity discrepancies or by the nozzle being partially blocked prohibiting the sensor from printing correctly. Figure 5 (b) illustrates drop misbehaviour that occurred randomly, but is seemingly caused by the residue generated by the ink around the nozzles. The automatic nozzle cleaner of the printer does not clean the nozzle exit surface completely resulting in the residue. When manually cleaning the nozzle surface, particles surrounding the nozzles can enter the nozzles and clog it. Figure 5 (c) shows a gap in 50 µm vertical line. The printer prints horizontally which creates a high probability for gaps in vertical lines due to the printer missing drops. Although the gap in Figure 5 (c) is a rare occurrence, it can be avoided by increasing the width of vertical branches that do not significantly influence the capacitance generated by the sensor. Another solution is to reprint another layer of the same sensor over the previous sensor in order to fill the gap. The observations made in Figure 5 can cause repeatability problems when printing several sensors. Figure 6 shows correctly printed IDE pairs, converted using 25 µm drop spacing and characterised cartridge parameters. Figure 6 (a) and (b) shows that complicated designs with small feature sizes, sharp corners and high resolution can be repeatedly printed. Figure 6 (c) is an image of an entire sheet of correctly printed IDE pairs.

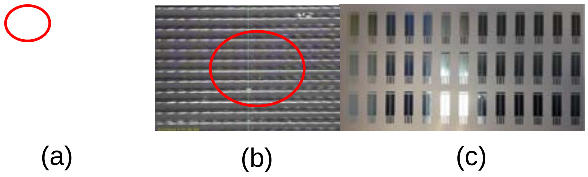

Figure 6 - Examples of the sections of a correctly printed sensor, including the sharp corners (a), small feature sizes and has a high resolution (b) that is repeatedly printed correctly (d) using a 25 µm drop spacing.

After taking into account the factors discussed, an adequate printing reliability can be achieved over repeatable printing runs of the biosensors. However, a curing process is required after the biosensors are printed, and this process also influences the effective yield of reliable printed biosensors

3.4 Curing refinement

Thermal curing is used to cure the printed biosensors. This process is required in order make the ink and therefore the printed biosensors conductive. During the thermal curing step, the tetradecane solvent evaporates first, followed by the resin binder that evaporates at higher temperatures. This leaves the silver particles in direct contact with each other, creating a conductive path in the biosensor structure [9].

The recommended thermal curing of the Harima NPS-J ink is 220 ˚C for 1 hour. However, the Epson photo paper burns at high temperatures. It was discovered that sensors that have not been cured became more conductive over time, when left at an ambient temperature. After two weeks the conductivity of two of the sensors increased 10 fold, after these two sensors were cured at 60˚C for an hour. This indicates that lower curing temperatures over a longer time will sufficiently cure the sensors. In initial tests, the curing temperature was lowered to 150 ˚C. This lead to either the paper coating cracking, or the adhesion of the ink to the paper decreasing to such an extent that the ink delaminates. This delamination can be due to different material temperature coefficient expansion (TCE) rates of the paper and the glossy paper coating. In both these scenarios, the affected sensors are rendered useless. Figure 7 shows an example of these defects.

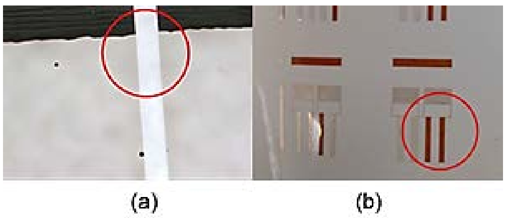

Figure 7 - The effects of curing at 150˚C on the printed sensors lead to (a) the photo paper coating cracking and (b) the silver ink delaminating.

Several tests were performed at different curing temperatures over a period of 2 hours in order to measure the resistance of an IDE [9]. However, the resistance of a correctly printed IDE is infinite, therefore the resistance over the 100 µm vertical line of the IDE was measured and is displayed in Figure 8.

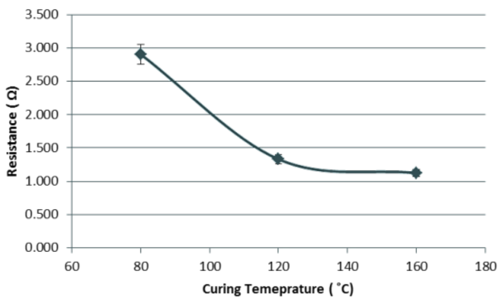

Figure 8 - Resistance measurements cured over various temperatures for two hours.

According to the Harima NPS-J brochure, when curing at 220 ˚C for 1 hour the resistance of a similar track should be approximately 1.4 mΩ, however, it is not specified what substrate was used, and such a high curing temperature is not feasible when using a paper-substrate. The sensors that were cured at 120 ˚C for two hours did not delaminate. Although some cracks still appeared, the occurrences of the cracks were rare. At temperatures lower than 120 ˚C the increase in resistance is more radical. Taking all the above into account, it was decided that the best thermal curing occurred at 120 ˚C for two hours. It was also observed that if the sensors were left at an ambient temperature after curing, the adhesiveness of the silver ink to the paper, and thus the ruggedness of the sensor, increased. After curing, the conduction of the sensor was tested using a Resistance, Inductance and Capacitance (RLC) meter. This was done to check if the respective sensors had open circuits as well as to identify and eliminate any sensors that had short circuits.

4 RESULTS AND DISCUSSION

When taking the all the above mentioned factors into account, certain observations were made that help refine the manufacturing processes of not only printed biosensors, but printed electronics in general.

When converting the design file to a bitmap file, a drop spacing should be selected that is equal to a factor larger than 1 of the minimum feature size, as well as smaller than the drop diameter. This is especially important when working with a small feature size. Vertical lines within the design should be at least twice as thick as the drop diameter. The yield of the first batch of full sensor designs was 28.01 % and the second batch was 53.85%. The large number of branches in the design increases the risk that an incorrectly dispensed drop can short an entire IDE pair, therefore lowering the yield. Some cracks that formed as a result of high curing temperatures were also present on the paper, which led to the decomposition of some sensors. However, when taking this into account there still exists a large difference between the two yields. This was due to the discussed manufacturing process being optimised after the first batch. The following list summarises the optimised printer specifications:

- Waveform:
  - Slew rate : 0.65
  - Duration : 4.096 µs
- Meniscus point : 3 (ref H_2O)
- Nozzle temperature : 33 ˚C
- Platen temperature : 33 ˚C
- Drop spacing : 25 µm
- Nozzle voltage : 19 V

This list can be altered depending on the desired printing results, as described. The optimal thermal curing for the biosensor is 120˚C for 2 hours. After the above steps were completed, several biosensors were manufactured, an example of which is shown in Figure 9. The total length of the IDE pairs are 29 mm consisting of 388 branches with the width of each IDE pair being 5 mm.

Figure 9 - Example a manufactured biosensor.

Laser profilometry was performed on the manufactured biosensor to analyse the sensor structure. This was done using a confocal laser scanning microscope (Zeiss LSM5 Pascal). Figure 10 shows that the branch thickness of a IDE is 50 µm; the tracks widths are between 50 µm and 55 µm wide; the spaces are between 44 µm and 49 µm in width and the length of each branch is approximately 4.8 mm .

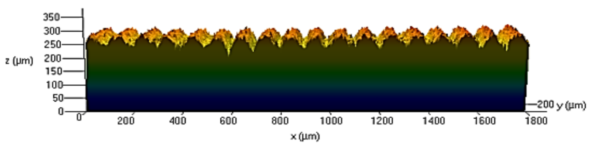

Figure 10 - Profilometry of the printed biosensor.

5 CONCLUSION

The manufacturing of the paper-based E.coli sensor showed that there are various factors that has to be taken into account and resolved when developing products that require small feature sizes and high repeatability, at a fraction of the time and cost of well-established technology platforms. When using ink-jet printing the small dimensions of the nozzles allow printing of small feature sizes consistently, if the cartridge settings are properly characterised.

The designs should be correctly converted, the ink must be properly stored and handled and curing temperatures may have to be altered when a substrate such as paper is used that fail at high curing temperatures. When considering a digital factory mind-map, this paper-based E. coli biosensor is still in its product development phase. The next step is to characterise and optimise the sensor, in combination with antibody, by doing several tests with different concentrations of E. coli present in a water sample. By refining the above mentioned manufacturing processes it not only allows for rapid prototyping and easily implementing design changes that accelerate the design process, but will also inherently accelerate large scale manufacturing in the future.

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7 BIOGRAPHY

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Additive Manufacturing for New Value Added Thermal Forming Process Chains

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Abstract

For *productive* and *high quality* thermal forming manufacturing *processes, conformal* tempering principles *have* opened *up* new possibilities. In the entire application field of conformal *cooling, most* industrial *applications* are related to the injection moulding procedure. *The* so-called variotherm requirements for high-quality surfaces of thermoplastic products *particularly offer* a new challenge for injection moulding. *Here, the* first successful application of ceramic heating elements with *geometrically complex* surfaces will be demonstrated. Best *suited to* the progress in these fields is the utilization of the advantages of the *latest functionally optimised* shell construction in *conjunction* with thermal simulations *of behaviour* and strength. *For efficient* improvements *in this* new tool concept, we have developed *what we term the* "*functionally optimised* shell construction principle". The thermal and mechanical demands of the injection moulding tool components require a *sound* theoretical foundation. These requirements *can* be *fulfilled successfully* with the simulation software SolidWorks. For the general tool *concept,* including filling *simulation,* the *well-known* Moldex 3D-Software *was used successfully*. *All of these discoveries are demonstrated using* selected examples.

Keywords

Rapid Tooling, Additive Manufacturing, Conformal and Variotherm Tempering, Injection Moulding

1 INTRODUCTION

Tempering of injection moulds is very important to improve the injection moulding cycle. *Optimisation offers higher-quality injection moulded parts and greater safety in the injection moulding* process.

In the tempering process, it is important to know the heat flow rates in *a* tool *during a single* cycle. Figure 1 *shows two temperature profiles in graph form.* Both *represent* processes *for* producing thermoplastics. The dark blue *line represents variotherm* tempering and the light *blue conventional* tempering. Above the profiles the supplied *and dissipated* heat flows are shown. Below the profiles the different phases in an injection moulded process are identified.

With variotherm tempering, it *is* possible to increase the surface temperature of the cavity in the phase where the injection tool is open*. Additionally, the heat flow is better* in the injection and cooling phase because of the *contour-based cooling.*

Improvements through variotherm tempering:

- The moulding compound cools down *more slowly* at the surface of the cavity, *and* the injection pressure can be reduced.
- The injection mould can be better filled with the moulding compound.
- The surface quality *is improved*.
- The dimensional stability will be better.
- Reduction of waste

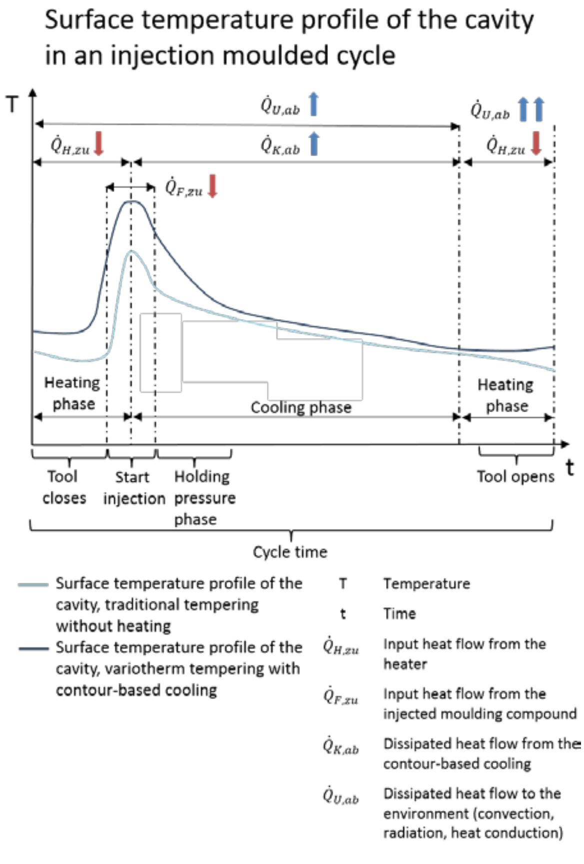

Figure 1 - Surface temperature profile of the cavity.

2 STATE OF THE ART

The *following two* tables show heating systems (Table 1) as well as cooling systems (Table 2).

Method		Characteristics	Advantages	Disadvantages
Conventional heating		Conventional crafted heating channels Medium: mainly water (to 160 °C), also oils	Inexpensive Easy to manufacture	Poor/ uneven heating close cores Uneven distance between heating channels and the cavity wall
Electrical resistance heating [3]	**Cartridge heaters [4]**	Filled with highly compressed *magnesium*	Surface load to 50 W/cm² *Less* expensive *than* ceramic heaters Easy to integrate at the Tool	Geometry technically restricted
	Ceramic heaters [5]	Consisting of silicon- or aluminium nitride	Surface load to 150 W/cm² Geometry technically unrestricted	More expensive than cartridge heaters (five times higher)
Induction	**General**	*Frequent strong electric currents in a coil*, *resulting in* an alternating electromagnetic field, which induces eddy current → Joule heating	High heating rates achievable	*Inductor design* is very elaborate and complicated

Table 1 - Heating systems [2]

Method		Characteristics	Advantages	Disadvantages
Conventional cooling [7], [8], [9]		*Conventionally* crafted cooling channels Supplemented with additional elements	Inexpensive Easy to manufacture	Poor/ uneven cooling Uneven distance between cooling channels and the cavity wall
Contour based cooling	**General**	Layered structure Cooling channels *largely follow* the contour of the cavity	Very good adjustment of the cooling channels to the wall of the cavity *Equal* cooling of the hole cavity	More expensive *than conventional* cooling
	Contura/ Integrat 4D [6], [10], [11]	Layered structure *Bonded* by diffusion bonding or vacuum high temperature brazing	*Less expensive* than SLM	*Process-related* limits *on* design possibilities
	Selective laser melting/ Laser Cusing [12], [13]	The powder is deposited layer by layer into the mould and adheres by melting	No design limits Optimal adjustment on the cavity wall	Very expensive Small cooling channels can *become* clogged *when* using water
Materials with different thermal conductivities		Improved *heat* dissipation *due to increased* thermal *conductivity*	Increased thermal *conductivity*	Only in combination with other methods

Table 2 - Cooling systems [2]

3 GENERAL FACTS

The reference object is a traditional constructed injection mould. *Based on the principle of “functionally optimised* shell construction*”,* this tool *is* equipped *with variotherm* tempering. The heating system consists of *ceramic* heaters and the cooling system *is made up of contour-based* cooling channels. The construction*,* as well as the simulation*, is* done with the software SolidWorks. The variotherm tempering *is* installed only on the die half of the mould cavity. *To integrate such a system on the other side would be very complicated and not worth the effort.* Investigations have shown *that variotherm* tempering of only one half of the tool has nearly the same *effect* as tempering both *halves*. The left picture in Figure 2 shows the die half of the mould cavity, which is split *into the* shaping tool, shell and stabilizer. The shaping tool shell includes the cooling channels as well as the gaps for the ceramic heaters (right picture in Figure 2).

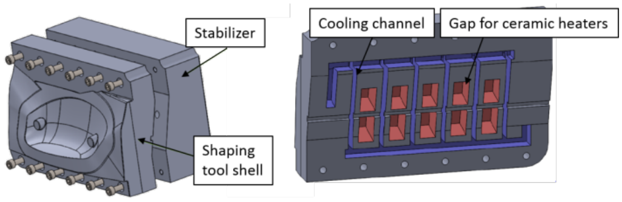

Figure 2 - Die half of the injection mould [1].

3.1 Cooling Channel

The channels have a rectangular cross-section, so the surface *of* the cavity is bigger *than it would be if drilling were used*. *This* increases the heat dissipation. Figure 3 on the left side shows how the cooling channels follow the freeform surface. The cooling channels *are* manufactured by spark eroding with a graphite electrode.

3.2 Ceramic Heating Elements [14]

The material *used for* the injection mould is heat resistant steel (1.2343)*. This* metal has poor *thermal conductivity* properties. The ceramic heaters *are* installed in aluminium matching elements. The surface *of* the cavity *is larger* and aluminium *has higher* thermal conductivity. For the aluminium matching elements, different variants have been developed. Figure 4 on the right side shows a targeted variant. Several elements *are* installed in one groove. *Simulations have been used to in tests to ensure* that no critical stresses occur.

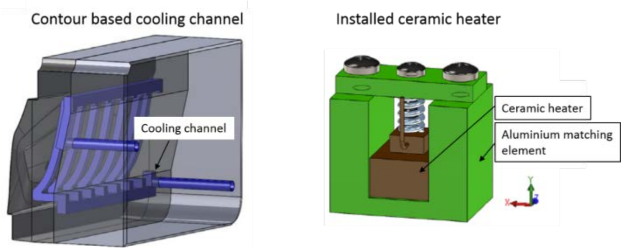

Figure 3 - Tempering elements [1].

4 CONCEPT DEVELOPMENT AND SIMULATION WITH SOLIDWORKS

Altogether, three *options* are considered in relation to the layout *of* the cooling channels as well as the ceramic heaters. The first *option* (see Figure 4, left) consists of ten ceramic heaters (14 mm x 14 mm) and six cooling channels (8 mm x 8 mm). A thermal simulation has *shown uneven* cooling, because the distance between the cooling channels is too *great*.

In *the second option,* the tempering elements are fine meshed (see Figure 4, middle). It includes twenty-one ceramic heaters (6 mm x 6 mm) and nine cooling channels (8 mm x 8 mm). The cooling is now *even*, but there are *many* parts *that* must *be* installed in the mould cavity and *it is difficult to control this technology.*

Option three is a compromise between *options* one and two (see Figure 4 right). It includes fifteen ceramic heaters (10 mm x 7 mm) and seven cooling channels (8 mm x 8 mm). The thermal simulations have shown that *this is* the most reasonable variant for the variotherm tempering.

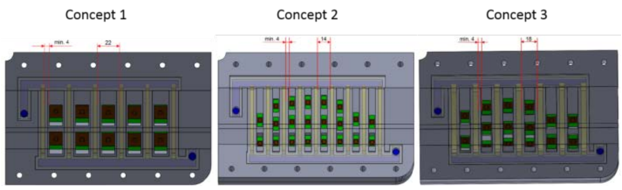

Figure 4 - Concepts [1].

4.1 Thermal design simulations

The first investigations were simulations of the cooling process. All *of the* selected *options* were compared. *The formation* of the temperature field after a cooling period of twenty seconds *was a deciding factor.* The *starting* temperature of the cavity was *an even* 130 °C. *Other limiting conditions, such* as *the* heat transmission coefficient *and material, among others,* were defined. *Heat transmission into* the environment was *ignored*. *The* comparison between the temperature field *in option* three *and conventional* cooling *is important; this is shown in* Figure 5. The temperature field *in option* three is more *even than* the conventional method and the average temperature is lower. The cooling conditions are better for the quality of the injection moulding part.

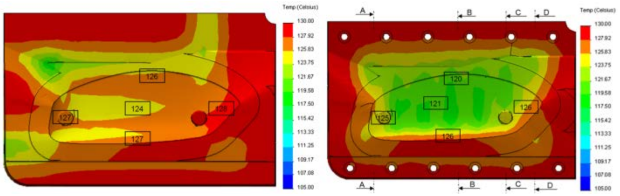

Figure 5 - Temperature field after cooling process [1].

Other investigations *of the heating process were also done*. At the start of production the injection mould is cold. At this *point many* injection moulded parts *have low surface quality* and are rejects. *Thus,* it is necessary to prepare the injection mould with a *warming-up* phase. The target of these simulations *was to determine how long it takes* to *raise* the temperature from 20 °C to 110 °C (glass transition temperature from ABS).The result of the simulations *indicated* that with ceramic heaters it is possible to reach this temperature after 22.5 minutes.

The last thermal *simulations* were investigations *depending on* the activation time of the ceramic heaters. Every simulation took ten injection moulding cycles. The first simulations *showed* that it is possible to reach *a* temperature of 135 °C. *To do this*, the activation time *for* the ceramic heaters before the start of the injection varies. Figure 6 shows the *results*. The longest activation time *lasts for* 40 seconds. After three injection moulding cycles, a temperature between 128 °C and 130 °C can be reached. *Cooling* of the injection mould can be prevented. Because of the additional heat flow *from* the ceramic heaters, the cooling time will be longer. An activation time of 5 seconds means an increase *in* the cooling time of nine seconds. *To achieve* better surface quality, it *is* recommended that the ceramic *heaters be* activated before opening the injection mould and *switched* off in the middle of the holding pressure phase.

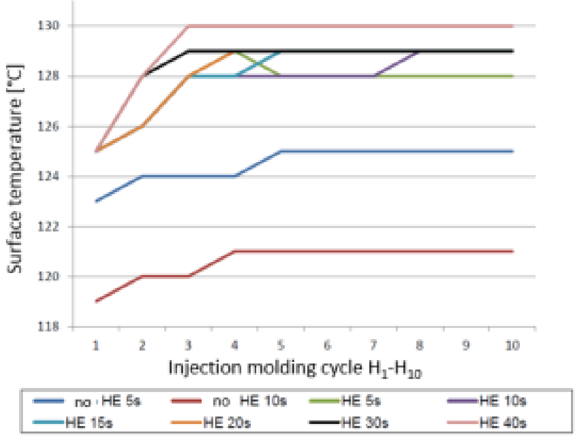

Figure 6 - Investigations depending on the activation time of the ceramic heaters [1].

4.2 Component strength simulation

After *determination of the load for* the injection mould and the *modelling*, material data and other general conditions, as well as the mounting of the model, *can be* defined and checked. Four load cases were considered.

In load *cases* one to three, subordinate problems are considered. In the *first*, the cavity mould was *stressed* with the clamping force of the tool. In the second load case, the injection mould was *stressed* with the injection pressure. And in the third, the tool *receives a thermal load* at the point of the injection. In all load cases the tensions as well as the deformations were considered, *as well as* the bolted connection. All strains were *non-critical* and the deformations *were* very *slight*.

4.3 Load case 4

This load case involves load *cases* one, two and three, *because* in reality all *of the* load cases *act in sum in* injection moulding. Figure 7 shows the deformation as the result of the strains. The maximum deformation on the bottom edge of the cavity is 0.091 mm. *More critical, however,* is the relative deformation of 0.04 mm between *the* bottom and the upper edge of the cavity. It is possible that the moulding compound *may be over-moulded.* Countermeasures *might include* a higher clamping force, or the *optimisation* of the tempering *may* be necessary. The maximum strain *on* the bolted connection is 309 N/mm², which is below the elastic limit of 600 N/mm². The maximum strain of the injection mould is 750 N/mm², which is below the elastic limit of 1910 N/mm². *Given these* tensions *and* deformations, *component* failure is not expected. More load cases were investigated, but they are similar *to load* case four. The principle *of* "*functionally optimised* shell design" can be *realised* in practice.

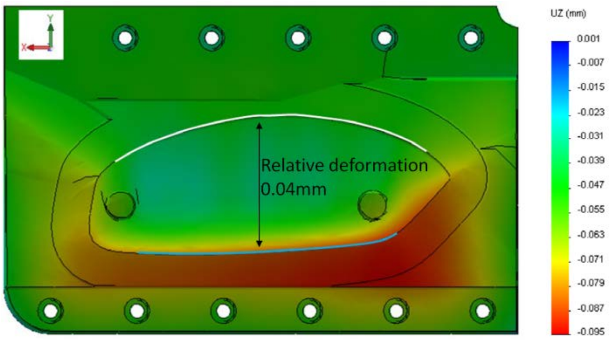

Figure 7 - Load case 4, Deformation diagram [1].

4.4 Injection moulding simulation with Moldex 3D

Moldex 3D *is simulation* software for injection moulding. It is possible to simulate single phases of the injection moulding *cycle, such as* injection (*the* filling stage), *the* holding pressure phase and *the* cooling phase. Questions concerning tensions, deformation, *fibre* orientation, *and* properties for structure or material can be *analysed*, verified and *optimised*. Negative developments can be avoided.

Before starting the production of the injection mould, it is important to perform a simulation. With this software, mistakes in mould design can be avoided. The simulation *was* carried out by the firm SimpaTec GmbH. *The goal was to compare conventional* tempering *and variotherm* tempering and to *find* information about injection pressure, filling cavity, moulding accuracy and deformation.

The simulation shows that the average surface temperature of the cavity increases (see Figure 8, left). The temperature range *for* conventional tempering is 75.5 °C to 85 °C and *for variotherm* tempering is 80 °C to 93 °C. This difference is the result of the activation of the ceramic heaters in the injection moulding. *It can be inferred that* the form filling and moulding accuracy will be improved through the higher wall temperature of the cavity. The injection pressure falls to 15 bar. *This means lower* stress for the injection moulding. *A check for* deformations *yielded* shape distortions *with* a maximum of 0.78 mm in the outer areas (see Figure 8, right). *In* this area the variotherm tempering is not *optimised for* the form of the cavity and must be improved.

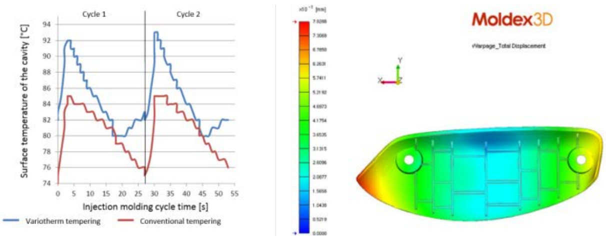

Figure 8 - Investigations with Moldex 3D [1], [15].

5 *SIGNIFICANT* RESULTS *OF UTILISING* IMULATION SOFTWARE

In carrying out the investigations, it was possible to *adapt*, according to the principle "*functionally optimised* shell construction", a conventional injection moulding *in shell* construction *with* variotherm tempering, which consists *of contour*-based cooling and ceramic heater chains.

The implementation of the *contour-based* cooling could only *be* partially achieved. The thermal simulations have shown an *even* temperature field and cooling. *However,* in the outer areas the deformation simulations show a shape distortion of 0.78 mm. It *makes sense* to improve the cooling channels in this area to reduce the distance between the cooling channels and the cavity.

The integration of the ceramic heaters increases the average surface temperature of the cavity *by* 8 Kelvin. Because of *this*, the form filling and the dimension stability were improved and the injection pressure was reduced. While the injection mould is open, the surface temperature can be *maintained* with the heaters. With the ceramic heaters it is possible to reduce *the number of reject parts* at the start of production *by* heating the injection mould to a specific temperature *before beginning*.

Deformations and tensions *on the mould cavity* because of the injection moulding were investigated. The highest *incidence* of strain results from the different temperature gradients. The tensions are below the tensile strength of the injection mould and the deformations were *considered non-critical*.

To be efficient in use, the injection mould must be further improved.

- To *optimise* the cooling *circuit, fluid* dynamics make sense.
- Mounting and regulation of the ceramic heaters
- Determination of *the* heat transfer coefficient

6 SUMMARY

High quality plastic products require the *utilisation* of new principles and tools *over* the entire value added process *chain*.

To obtain efficient improvements *in* the new tool *concept, functionally optimised* shell construction in *conjunction* with the first application of ceramic heating elements was developed for *geometrically complex* surfaces. The thermal and mechanical demands of the injection moulding tool components require a *suitable* theoretical foundation. These requirements *can* be *successfully* fulfilled with the simulation software SolidWorks and Moldex 3D. These tasks are the main *focus* of the research group at the "Centre for Applied Research and Technology (ZAFT)" at the University of Applied Sciences Dresden.

The general topic is a research project *within* the *framework* of the German Central Innovation Programme for SME (German abbreviation ZIM). *Adoption* and experimental tests *necessitated some modifications by industrial partners*. Some *discoveries* will be demonstrated with selected examples.

7 ACKNOWLEDGMENTS

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Federal Ministry of Economics and Technology

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9 BIOGRAPHY

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World of Tooling

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Abstract
Tools and dies are the enabler for mass production of components and end products. The manufacturing of tools and dies is the essential task of the tooling industry. The proceeding globalization leads to new sales and supply markets around the world. As a consequence, production sites of individual companies in conjunction with their demand for tools and dies are increasingly internationally spread. New tooling markets that first serve local demands become eventually interesting for international sourcing options. In order to address international markets for the supply of local production sites or utilize them for international sourcing, it is important to have an in-depth understanding of the different markets. However, up to the present no scientific approaches exist, which compare the world's most important tooling countries on a profound data basis. The Laboratory for Machine Tools and Production Engineering WZL has developed an approach to transform general and tooling specific data from countries all over the world into utilizable knowledge by evaluating their current tool and die making competence and their future potential. The results of the developed approach are four distinguishable clusters of tooling countries. In order to illustrate the results a tooling radar with the dimensions competence and market size was developed. The tooling radar shows the "Rising Stars" with a small market size and a low tooling competence but with high future potential. The "Rookies" are characterized by a medium tooling competence but a small market size. The group of the "Established" countries have a medium to high tooling competence and a medium market size. The "Allstars", the fourth group of countries, have a high tooling competence as well as a big market size. The radar can be used by producing as well as tool and die making companies to support future strategic decisions in terms of international sourcing of tools and dies.

Keywords
Market Intelligence, Tooling radar, Toolmaking, Tool and die industry, World of tooling

1 INTRODUCTION

Across all industries, manufacturing companies from high-wage countries, especially the tool and die making industry, face a growing competitive pressure and a change of their economic environment. This is a result of the growing competitive strength of companies who originate from low-wage countries [1].

So far, companies from high-wage countries have been able to establish a market leadership due to the qualitative superiority of their products. However, significant challenges – especially the cost pressure triggered by the increasing internationalization and the reliable tool supply for foreign productions plants – compel manufacturing companies from high-wage countries to major adoptions. These adoptions include in particular the utilization of markets with lower factor costs and shorter distances between customer and supplier. Yet, relocating production volumes to foreign markets rarely achieves the desired results. Companies see themselves confronted with production critical problems, for instance fluctuating levels of quality and poor due date reliability caused by an insufficient tool supply.

These problems result of insufficient Market Intelligence and a missing approach to compare the world's most important manufacturing countries on a profound data basis. This also applies to the tool and die making industry.

Therefore a systematic approach for building up Market Intelligence for the relevant markets of the tool and die making industry will be introduced on the following pages.

1.1 Challenges for the tool and die making industry

The tool and die making industry is one of the key industries in the manufacturing sector, due to its crucial role as the enabler of series production [2]. It is currently confronted with three major challenges, caused by changes of the economic environment: an increasing product derivatization, shorter product lifecycles and globalization [3].

As a result of the increasing product derivatization in combination with shorter product lifecycles, companies currently face a growing number of product variants, while the production volume per variant is decreasing. Since the budget for development and production has not been increased according to the higher number of variants, the available budget for each variant is smaller. As the costs for the tools, which are needed for the production, constitute a significant share of the overall production cost, the tool budget is reduced by the customers. Therefore tooling companies have to offer their tools at lower prices [4].

Additionally the globalization leads to new sales and supply markets around the world with new competitors and significantly lower factor costs [5]. Over the last years, these competitors were able to enhance their quality standards and technological competence and with that the complexity of the tools. This results in the disability of tooling companies from high-wage countries to differentiate solely over quality superiority and complexity.

To face these challenges, tooling companies from high-wage countries need to benefit from lower factor costs and relocate production volumes into low wage countries such as China or Mexico. As a consequence, production sites of individual tool and die making companies are increasingly internationally spread. However, decisions on relocation are often based on insufficient market knowledge.

A reduction of risk as well as a sufficient way to seize opportunities, resulting from market changes requires an adequate insight on local market conditions: Market Intelligence.

2 MARKET INTELLIGENCE

The scientific literature contains different definitions of Market Intelligence, depending on the context. In this paper, Market Intelligence is seen as the motivation dependent insight of a defined market that provides the basis for strategic decision making.

In general, various types of markets can be distinguished, for example by the direction of transaction, type of goods, regional expansion or distribution of power [6]. For this paper, especially the direction of transaction of goods as well as the regional expansion are of significance. The focus lies on the provision of tooling components in foreign markets and the utilization of those markets for international sourcing.

Market Intelligence results of the systematic process of acquiring and analyzing information of the business environment and its changes. This enables companies to derive organization-specific reactions and assess the impact of events in their economic environment. It therefore helps to prevent poor decision making based on a lack of insight and enables companies to seize promising business opportunities. As a consequence, Market Intelligence is an enabler of effective decision-making, cost savings and sustainable development. It additionally minimizes the risks that accompany every decision.

Market Intelligence can be distinguished between continuous and event-related Market Intelligence. Continuous Market Intelligence is necessary for the constant insight on current market developments, e.g. a new business model of a competitor. This requires a team of experts that is permanently integrated in the organization and focuses on the extraction, analysis and preparation of relevant data.

Event-related Market Intelligence is characterized by a narrow field of insight with a high level of detail. It is required for decision making situations, which are lacking accurate information. The planned relocation of production capacities can be mentioned as an example for event-specific Market Intelligence [7].

2.1 Importance of Market Intelligence

Market Intelligence is business critical for manufacturing companies for two reasons:

The operating environment of organizations experiences an increase of its complexity and dynamic. To successfully manage these factors accurate information to build up individual insights as platforms for sustainable decision-making is needed [8].

Simultaneously, a flood of information is at the company's disposal and inhibits it from distinguishing and processing what is relevant for their decision making purposes. This „information-disconnect“ will increase in significance in the near future due to the growing availability of information as well as challenging trends such as Big Data.

Thus, the process of obtaining relevant and accurate information and transferring it to insight that can be used for the company's decision making becomes increasingly important.

2.2 Existing approaches

In the scientific literature there are some approaches for event-related Market Intelligence that describe a company's business environment and its key driving factors with regard to their strategic decision-making. These include the following three models:

- *Porters Five Forces*: This is a framework to analyze the level of competition within a market and develop business strategies. It describes five competitive forces that define a market: Threat of new entrants and substitutes, bargaining power of customers and suppliers and intensity of competitive rivalry [9].
- *The new St. Gallen Management Model:* This is a model that serves as a management guideline for the systematic classification of challenges, fields of action and fields of decision. The model takes six management dimensions into consideration: development modes, structuring elements, processes, environmental spheres, interaction topics and stakeholders [10].
- *PESTEL – Analysis:* The PESTEL analysis is an external environmental analysis that evaluates how affected a company is with

regards to economic, political, sociological and technological factors [11].

2.3 Evaluation of existing approaches

The evaluation of existing models in terms of applicability for an entire market evaluation and in terms of applicability for the tool and die making industry shows that these approaches are not suitable for a detailed analysis of the business environment of the tool and die making industry. The described approaches are kept generally and are – due to their low level of detail – not suitable for small and medium enterprises (SME) like tool and die making companies. Even though they include important factors that are relevant for Market Intelligence, none of these models are capable of creating an overview on various markets of the tool and die making industry. Therefore up to the present no scientific approach exists which compares the world's most important tooling countries on a profound data basis. This results in a need for a tailored approach for the tool and die making industry.

3 WOT–APPROACH

The scientific literature currently lacks of an approach that enables companies to compare the world's most important tooling countries on a profound data basis. The WOT-approach (**W**orld **o**f **t**ooling approach) builds up Market Intelligence through analyzing market specific data for certain markets and makes them comparable through displaying them in a clustered tooling radar. By including tool and die specific data, the radar not only allows statements on markets. It additionally enhances the usability of the approach for the tool and die specific industry to support future strategic decisions in terms of international sourcing. This approach will be examined in the following section.

The approach of the WOT- approach consists of two major parts: First, general and tooling specific data from countries all over the world are transformed into utilizable knowledge by evaluating their current tool and die making competence and their future potential. The results of the developed approach are four distinguishable clusters of tooling countries. Secondly, the several markets are displayed in a tooling radar with the dimensions competence and market size.

The data analysis includes three steps. First, the country is analyzed on a market specific level. This includes key figures of the national economy. The second level is the industry specific level, which analyzes key figures of the manufacturing industry. Lastly, on the third level, the WOT- approach analyzes branch specific key figures. These are key figures that solely affect the tool and die industry branch.

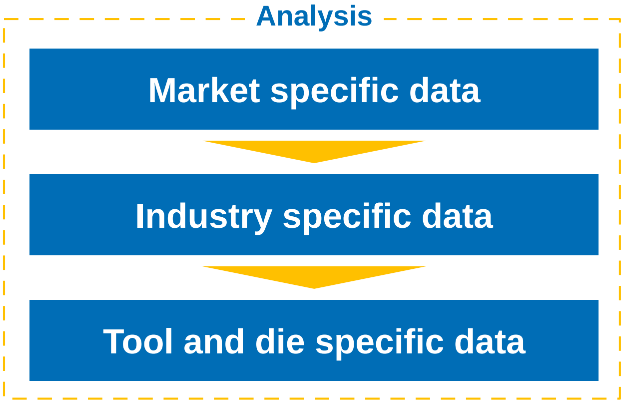

Figure 1 - WOT analysis

The focus of the examination lies on the comparability of the different markets. A detailed view on each market and its specifics regarding Market Intelligence is not part of this paper. Thus, a approach will be described that provides a generic overview on the qualification of markets for the tool and die industry.

3.1 Clusters of the WOT

The tooling radar's purpose is to classify the considered countries. Therefore the approach rates them with regards to the dimensions market size, competence and development potential. Afterwards the countries are plotted in a scatter graph with the dimension competence on the abscissa and the dimension market size on the ordinate. In the radar only countries are shown which are substantial for the worldwide tool and die making industry in the three mentioned dimensions. Countries with a very small market size, a very low tooling competence and a very low development potential are not shown in the radar.

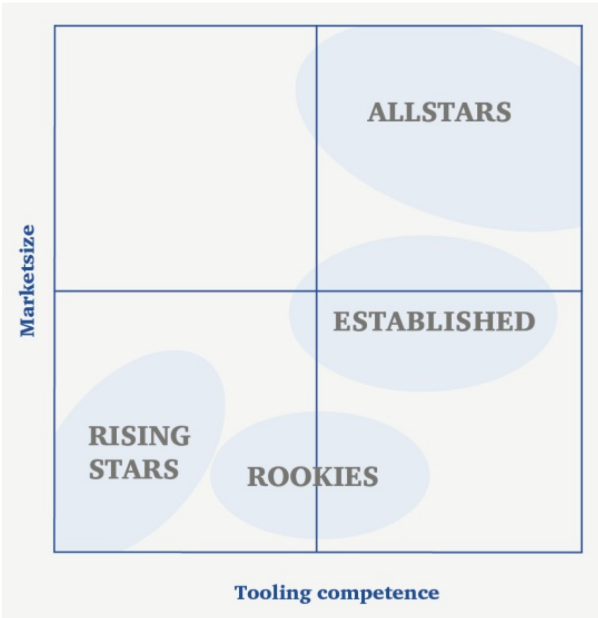

Figure 2 - WOT Clusters

To further enhance the structure and significance the radar is separated by a dividing line. The radar is divided into four different clusters: Rising Stars, Rookies, Established and Allstars. Each of these clusters embodies a certain market position from which business strategies can be derived. The allocation of the clusters is based on profound knowledge of the tool and die making industry in certain countries.

The “Rising Stars” are countries with a small market size and a low tooling competence like South Africa, India and Brazil. They possess high future potential in both market size and competence which makes them especially attractive for the utilization as new tooling markets.

The “Rookies” – countries like Turkey or Poland – are characterized by a medium tooling competence but a small market size. Countries of this cluster can therefore be utilized for international sourcing. Additionally the future potential of the dimension market size qualifies these countries for the supply of local production sites.

The third cluster is called “Established”. In this cluster countries like Italy, Canada and Switzerland are located with a medium to high tooling competence and a medium market size. These countries have a comparable tooling competence to the “Allstars”, but the overall market impact is lower. Complex tools with a high to very high quality can be sourced there.

Countries of the fourth cluster, the “Allstars”, have a high tooling competence as well as a big market size. This cluster includes the leading countries of the tool and die industry e.g. China, Germany and the USA. These countries can be used for sourcing complex and highly productive tools. The building quality and the efficiency of these tools are on a highest level.

3.2 Elements of the WOT–approach

In order to address international markets for the supply of local production sites or utilize them for international sourcing, an in-depth understanding of

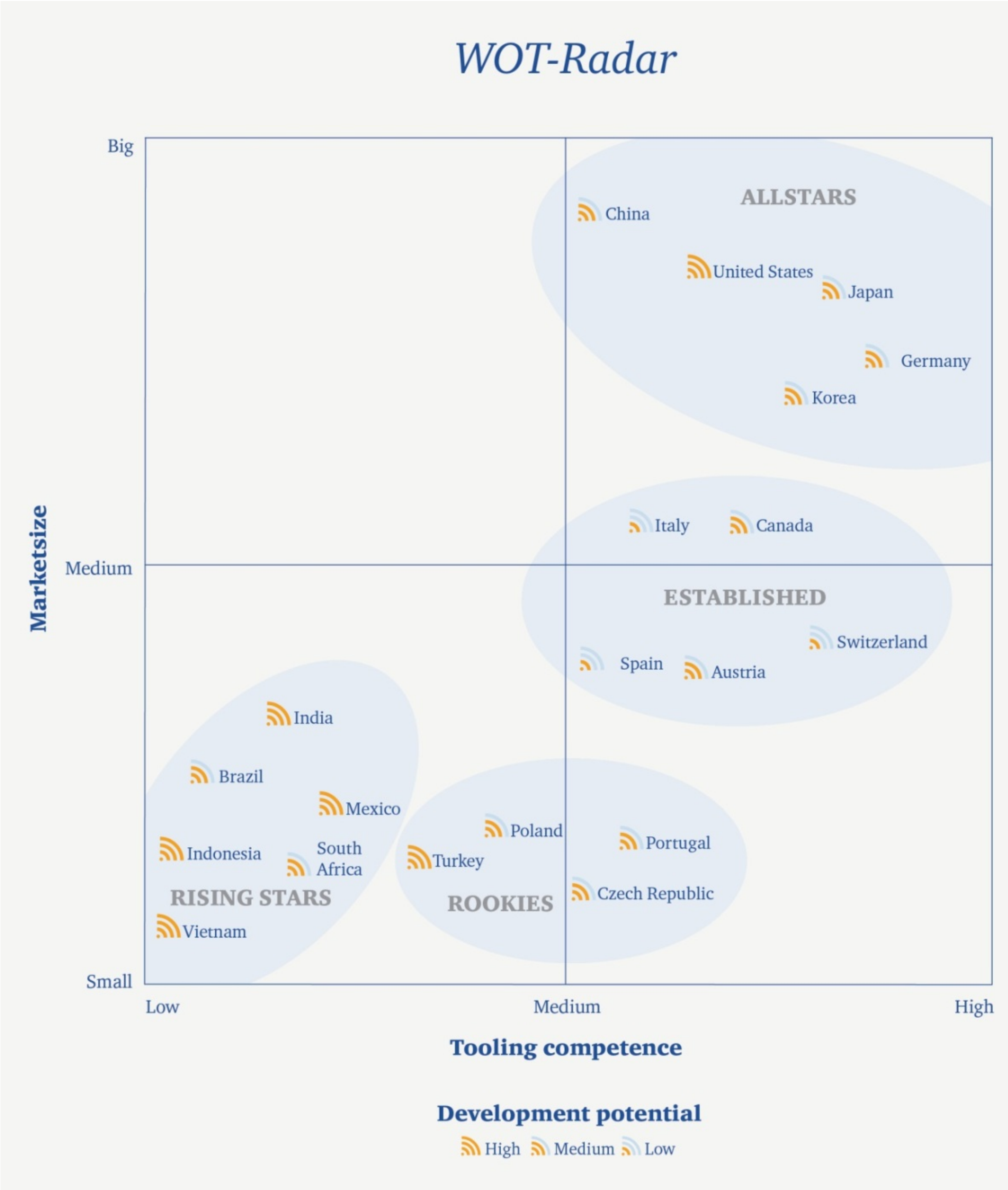

Figure 3 - WOT Radar

the different markets is necessary. Therefore companies need to gain utilizable knowledge of a countries tool and die making competence and its future potential. This knowledge can be derived by transforming general and tooling specific data from countries all over the world.

The WOT-approach serves for the analysis and evaluation of a country on a market, an industry and a tooling specific level. Each level is characterized by specific key figures. This data is then divided into three major dimensions – competence, market size and development potential. The several key figures are rated and combined to an overall score that is then displayed in the tooling radar.

Although the size of the cluster Allstars is large, only five countries are located in this cluster, China, USA, Japan, Germany and Korea. Germany has the highest level of competence in the whole radar, but Switzerland and Japan are very close in terms of tooling competence. Also five countries are located in the cluster Established. These countries have a comparable tooling competence to the Allstars, but due to the smaller market size, they are not sufficient for the cluster of Allstars. Portugal, Czech Republic, Poland and Turkey are called the Rookies in the radar. Portugal and Czech Republic are at a similar competence level like Spain and Italy, but their market sizes are considerably smaller. Mexico – located in the cluster Rising Stars – is very close to the border to the Rookies and has the chance to locate itself in the cluster of the Rookies, if they put a lot of effort in the tool and die making industry in the near future. Vietnam, Indonesia and India have the highest future potential in the cluster Rising Stars, but currently the tooling competence is at a low level.

3.2.1 Competence

The first dimension transforms general and tooling specific data into an overall assessment on the competence of a countries manufacturing sector and its tool and die making industry. The general data consists of political, economic, technological and social key figures. It is assumed that countries with poor political, economic, technological and social key figures can not dispose of a high tooling competence. In particular surpassing economical and technological key figures are indispensable presupposition for a high tooling competence.

Political key figures evaluate a country on how supporting the governmental structure and stability is for the manufacturing and the tool and die making industry. This includes figures like the ease of doing business, the globalization index and the hours of work required by law.

Econocmic key figures describe the environment of the current national economy and its future development. This includes key figures like interest rates, average wages, the country's assessment by ranking agencys and the Big Mac Index – an index to represent the purchasing power parity between two currencies.

Technological key figures give an insight on the technological development and standards of a country in terms of tooling competence. They evaluate a country's tooling competence with regards to the research and development, the number of patent applications in the tool and die making industry, the amount of researchers and other specific areas. A tooling specific technological-capability-figure, derived from the longstanding global tooling experiences of the WZL, is also one of key figures, which has been incorporated in the calculation.

Social key figures evaluate a country on its structure features like population structure and educational strucutre. They additionaly include associated trends like the demographic change.

3.2.2 Market Size

The second dimension evaluates a countries market size. It serves as an indicator for the market potential of a country. This is an important factor for companies that are planning on utilizing a country as a sales market.

The dimension combines key factors that are relevant to either the manufacturing industry or specifically the tool and die making industry. To evaluate the manufacturing industry specific market size general key factors e.g. share of global trade are compared and thereon rated. The tool and die specific market size is then evaluated based on goods movements. Export, import and production volumes allow a precise classification of the considered countries with regards to their tool and die industry. These key factors are then combined to an overall assessment on a country's market size.

3.2.3 Development potential

The third dimension describes the future development potential of a country in terms market size and tooling competence. The definition of this dimension is, in comparison to the first two dimensions, not a calculation of absolute numbers. It is rather a comparison between historical and current market figures. From a positive development of e.g. a growing national output or a rising export rate of manufactured goods can be concluded that the tool and die making industry will benefit in the near future. These information in combination with the existing market knowledge lead to the development potential for each country.

3.2.4 Evaluation

The WOT-approach assesses countries by ranking each key factor of the dimensions. Since the actual values of individual figures can not be offset against each other, a points system with points between 10 (best score) and 1 (worst score) is introduced. The span between the maximum value of a key figure and the lowest value is divided into 10 equal intervals (deciles) and the corresponding points for a market assigned. Deciles are one possible form of a quantile. Quantiles are statistical instruments that divide a total frequency of a sample into a given number of equal portions. A decile is one part of a distribution of ten groups with equal frequencies. To determine the final values of a market in the dimensions of market size, tooling competence and development potential, the mean value of all available key figures is calculated. This results in the possibility of ranking the considered countries with regards to the several key factors. This way the countries can be plotted in the tooling radar. That allows a profound comparison of the world's most important tooling countries on a profound data basis. For the calculation of the development potential in addition, the developments of key figures over a defined period are assigned to a points system with points between 10 (best score) and 1 (worst score) in the same manner as mentioned above.

4 CONCLUSION

The WOT-approach was developed to serve as the first scientific approach that compares the world's most important tool and die making countries on a profound data basis.

The approach of the WOT-approach consists of the transformation of general and tooling specific data from countries all over the world into utilizable knowledge. A country is evaluated on its competence for the manufacturing and tool and die making industry and its future potential. The results are then plotted in a tooling radar that allows the comparison and categorization of the considered countries.

The WOT-approach reflects a helpful approach to build up Market Intelligence in foreign countries and compare these countries. This accurate Market Intelligence provides the foundation for better decision making. While minimizing risks resulting of market changes, it supports companies to seize opportunities.

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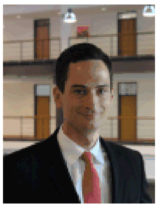

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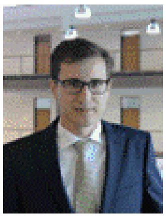

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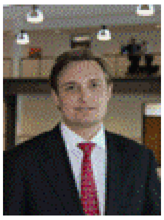

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Fast Forward Tooling

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Abstract
The tooling industry is one of the most important industries in the manufacturing sector due to its key role in the value chain between product development and serial production. In an increasingly global production environment the tooling industry stands in an aggressive competition which is characterised by rapid changes. The competition is intensified by the following major challenges: An increase in product variation, shorter product life cycles, and lower factor costs in emerging regions. To cope with the situation described and to gain a competitive advantage tooling companies have to arrange their value creation process more efficiently. In practice, companies need practical advise to fulfil this task. Existing approaches of production engineering in the context of lean management, industrialisation and digitalisation are often unsuitable for supporting the tooling companies. Those concepts almost exclusively lack of practical measures and are not easily adaptable to the small-batch production. At the WZL of RWTH Aachen the "Fast Forward Tooling"-approach has been developed. This systematic, highly practical approach is tailored for the tooling industry and supports companies to increase the efficiency of their value creation process. For this approach, the nine factors of success emotionalisation, construction kit, smart services, synchronisation, glocalisation (the idea of globalisation combined with the idea of local considerations), automation, innovative engineering, digitalisation and working culture were defined. The conscious design of these factors of success is the path to more efficient value creation and therefore helps tooling companies to be successful in future. Each success factor is illustrated by a practical example.

Keywords: tooling, digitalisation, efficiency, factors of success

1 CHALLENGES FOR THE TOOLING INDUSTRY

Due to its key role in the value chain between product development and serial production the tooling industry is one of the most important industries in the manufacturing sector [1]. The tooling industry enables the product development to design new products as well as the serial production to produce those products at a high quantity and economical prices. As a high-performance manufacturing sector requires efficient and highly productive tools [2], the tooling industry largely contributes to the economic performance of major economies [3, 4]. An increasingly global production environment and the resulting aggressive competition, characterised by rapid changes, are directly affecting tooling companies. The changes of the economic environment can be summarised into three major challenges. An increasing product derivatisation, shorter product life cycles and lower factor costs of global competitors [5, 6]:

Product derivatisation describes the trend to expand the product range through product varieties. The combination of increasing product derivatisation and shorter product lifecycles result in more product varieties with a decreased production volume of each variety. Hence, tooling companies are directly affected to manufacture more tools with differing designs in a shorter time. Furthermore, the tool costs constitute a significant share of the overall production costs as the product quantity produced with one tool decreases. That causes a more price sensitive purchasing behaviour of the tool customers.

The development of global markets is not only connected to high potential for tool makers from high-wage regions. Globalisation has led to new market players with significantly lower factor costs [7]. In the past, tool makers from high-wage countries where able to differentiate by their quality superiority. However, as global competitors caught up in both technology and quality, an altered path for differentiation is necessary. Promising approaches are a differentiation through a more efficient value creation process or through product-related services. A progressive number of tooling companies has also recognised the vast benefit connected to the relocation of production capacities.

However, as tooling companies make extensively use of hand crafting they are not sufficient for a sustainable differentiation in the cost-pushing business environment. Hence, the tooling industry has to use business differentiators in order to preserve competitiveness by increasing the efficiency of value creation. Tooling companies are often unable to cope with the situation described. There is a prevailing uncertainty about the topics that have to be addressed as well as the necessary measures. A regulatory framework supports companies to identify the fields of action while leaving the companies enough space to develop company specific solutions.

2 REGULATORY FRAMEWORKS IN TOOLING

In scientific literature, there are some approaches that describe regulatory frameworks for manufacturing companies. Regulatory frameworks represent complex systems, which illustrate aspects relevant to the system's behaviour. They show how the system is expected to respond on possible interventions [8]. Specifically applicable to the tooling industry is the value creation system for industrialisation which was developed at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University.

2.1 Existing approaches

The concept of industrialisation in the tooling industry was addressed extensively in recent years to support companies in the increase of efficiency. In this context, the adaption of lean principles which are usually applied in serial production to the tooling industry is a promising approach. *Klotzbach* has developed a value creation system (compare fig. 1) that supports tooling companies to industrialise their production and optimise their value creation [9]. The system consists of eight constituent fields.

The basis for the value creation system of industrialisation for the tooling industry contains the fields focus and cooperation. Tooling companies have to focus on their core competencies to succeed in an environment that is continuously growing more competitive. The focusing requires cooperation. Partners within the value chain of tooling companies are necessary to source external capacities and to increase the efficiency of internal manufacturing processes.

The first field of the nucleus is the standardisation of products. It aims at reducing the variety of components that are required to manufacture tools. There is usually a high potential for product standardisation in tooling which can often be realised by manageable effort. The standardisation of processes is based on standardised products. Its main target is the reduction of the variety of manufacturing processes. Standardised processes allow the employment of very few configurations for the manufacturing of tool components. A validated approach for standardisation of processes in the tooling industry has been developed by Kuhlmann [10].

Standardised products and processes enable the development and implementation of flow manufacturing in tooling. Flow manufacturing offers a high potential for improvements in efficiency as well as in transparency. The flow of the material determines the planning and scheduling as well as the production layout.

The last part of the nucleus, synchronisation, describes the coordination of process steps within the order fulfillment process regarding time and content. The overall aim is the reduction of delays and disposals.

Constant and short lead times, reduced inventory, high process stability and reliability, flexibility through rapidness, increased transparency and visual management can be named as main characteristics of a synchronised value creation processes. Concerning synchronisation in the tooling industry, an approach has been successfully developed and validated by *Rittstieg* [11]. Within the synchronised production the implementation of a clocked production is the supreme discipline. Components of different geometries and processing times are put together on a clock pallet in a way that enables the match of the processing time and the clock time. The necessary flexibility results of the interposition of decoupling points. Thereby, the components can be transferred to the following manufacturing sequence in a defined clock time, which results in a decrease of lead time and an increase of the adherence to delivery.

Product and process standardisation as well as flow manufacturing and synchronised production focus on the concrete value creation of the tooling industry. In addition to these core fields, the support of administrative departments, including controlling, calculation, compensation and purchasing is necessary for the realisation of a sustainable and holistic industrialisation. Furthermore, the motivation of employees is a crucial factor for the increase of performance and productivity [9].

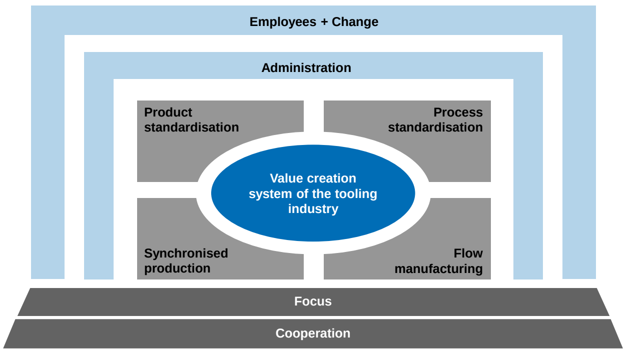

Figure 1 - Value creation system for industrialisation of tooling companies [9]

2.2 Evaluation of existing approaches

The competitive environment in high wage countries is forcing tooling companies to question current strategies. As a link between product development and serial production a paradigm change from craftsmanship to industrialisation is a basic requirement and is considered by existing approaches. The majority of tooling companies can be further characterised by the unique handcraft production. At present, the industrialisation approaches are applied by more and more tooling companies. However, new trends and challenges are highly influencing tooling companies and demand further adoptions of industrialised tooling companies. There is a need for a holistic approach, tailored for the industrialised tooling industry which considers the new trends and supports the right interpretation and operational realisation of companies.

3 FAST FORWARD TOOLING-APPROACH

At the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University a new holistic approach for the tooling industry has been developed. Based on the industrialisation of tooling companies, the Fast Forward Tooling-approach supports companies to counteract the rising competition and the new trends: It determines nine relevant factors of success that need to be addressed by the companies to consequently react to the challenges and stay competitive in a turbulent environment (compare fig. 2). To enable an efficient and purposeful approach, the specifics and requirements of the tooling industry need to be considered. For this purpose, the approach illustrates a tailored, industry specific beacon from which tooling companies need to derive company specific solutions. To validate the approach, a study was published by the WZL in which 72 tooling companies were questioned in detail to the relevant topics [12].

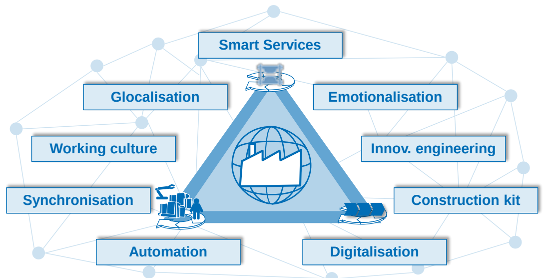

Figure 2 - The nine factors of success of the Fast Forward Tooling-approach

As a result, the Fast Forward Tooling-approach describes a successful tooling company which focuses on certain factors of success in the fields product, process and resources. The conscious design of these factors of success is the path to a sustainable competition.

3.1 Factors of success

To engineer a more efficient value creation chain, the three fields of product, process and resources must be taken into consideration. Products are the interface with the customer and illustrate the value generated. The processes create products and generate value, while the resources are the substance of the manufacturing company. Product, process and resources are interconnected and represent the structure of the success system for value creation. The Fast Forward Tooling-approach focuses on nine factors of success. These pick up trends and the latest problem-solving approaches for tooling companies. As product, process and resources are closely interdependent in value creation, so are the factors of success themselves. It is therefore hardly possible to achieve absolute excellence in all fields. The description of the factors of success will show that there are various options for shaping the factors. Each company must determinate the way it addresses each factor of success individually.

Smart Services

In tooling, there is an increasing change in the industry's identity that mainly affects the customer's perspective: The focus of the business models is no longer the tool itself. Instead, the manufacturing process which is enabled by the tool increases in significance. In the context of digitalisation, the service range is more and more extended by data-based services. In the study, two thirds of the companies surveyed that their previous business models would change radically in future years through digitalisation.

Smart Services represent the front end of the tooling company to the customer. Through a high degree of interaction of the tooling company with the customer as well as a systematic data analysis new knowledge can be generated. This knowledge can be commercialised by offering derived services. For example, the knowledge is used in product development to design the product in a way that is suitable for manufacturing. After the delivery of the tool the tooling company optimises the operating parameters in order to influence the application rate, the quality and the tool life cycle in a positive way. In future, the recorded data will increase in value and will become a trading good among and beyond the value chain.

Smart Services must be utilised to improve existing business models and develop new ones. Hereby, the tooling enterprises evolve from a pure tool manufacturer and supplier to an all-round provider and knowledge manager throughout the entire tool life cycle. Services such as quick reacting maintenance and repairs, the support of part development or the acquisition of the tool management of serial production will gain importance in the future as digitalisation provides vast chances for increasing the customer value connected to those services. Therefore smart services provide a high potential for differentiation from international competitors.

Emotionalisation

The second factor of success is emotionalisation. Emotions play an important role for purchasing decisions. Products are able to transport emotions in a targeted manner, convincing customers and securing their loyalty. However, in tooling marketing methods focus exclusively on technical details. Tooling companies must utilise emotionalisation to link the technical potential of their products with positive associations for the customer.

This emotionalisation is best realised through the creation of a brand and through a professional marketing concept. Linking the brand with a positive characteristic and thus a positive emotion increases customer loyalty and enables the acquisition of new customers. The key is the reflection of the technical quality in tool design and marketing. The result is the possibility for tool makers to increase their visibility.

Innovative engineering

A central service of tooling companies is the support of the customers product development. Here, the tooling industry faces constantly shrinking development cycles. As a result, prototypes must be developed faster and less expensive. In the future, the tooling companies must utilise their know-how to integrate into the product development at an earlier stage in order to master these shorter development cycles. In this context, services that go beyond the simulation of products and the production of prototypes are promising approaches. The enhanced simulation of processes and the definition of process and technology parameters to increase the process reliability are crucial. The virtual design of processes combined with a fast and low-cost production of prototypes through additive manufacturing transform tooling companies to drivers of innovation in terms of the product and the technology.

Nowadays, tooling companies attempt to generate new solutions in a structured way that constricts the creative freedom. Simultaneous engineering or development standards take the place of individual initiatives. In the context of cost savings, the validation of new products in a real setting is often dispensed. Instead, defined processes are utilised to ensure the application and manufacturing feasibility of new product solutions at an early stage.

In contrast, solutions should be initially designed, tested and optimised in short cycles, where the focus is on improving them before degrees of freedom are narrowed by requirements and restrictions. On the other side, many development projects are too complex to be expressed in a fully comprehensive plan.

Innovative engineering as the third factor of success allows tooling companies to combine aspects of structured engineering and disruptive innovation. Structured engineering is the professional project manager for the path to solutions. Defined development projects, stages and approvals make it possible to reliably take into consideration requirements and restrictions. Disruptive innovation creates freedom for new solutions. The development process is initially independent of the technical departments; solutions are designed disruptively, and tested without taking into consideration the full spectrum of existing requirements and restrictions. Development, therefore, represents the proactive exploration of new possibilities, without a clearly defined solution space.

Construction kit

The fourth factor of success is the design of construction kits. In tooling a major share of the non-shaping components of the tool can be standardised, while the shaping components of the tool have to be manufactured individually. The standardisation aims at reducing the variety of components that are required to manufacture tools. There is a high potential for product standardisation, as common tools are usually assembled of several hundred individually designed and manufactured components [13]. Due to a construction kit the standardised components can be combined to a customised tool which satisfies individual needs.
The standardisation of processes is based on standardised products. Its main target is the reduction of the variety of manufacturing processes. Standardised processes allow the employment of very few configurations for the manufacturing of tool components.

The standardisation of products and processes establishes the offering of construction kits. Construction kits resolve the tension in a range of products and services characterised by a maximum of internal standardisation and the highest possible level of individuality for the customer. Standardisation enables rapid, low-cost, reliable product developments and allows identical production sequences utilising uniform operating equipment. The individuality perceived by the customer on the basis of visible and experienced product characteristics and additional services can be determined by concentration on defined individualisation characteristics.

Digitalisation

The implementation of modern information and communication technologies in increasingly industrialised tooling companies contributes significantly to the competitiveness. However, the potentials of digitalisation are not exploited in tooling companies in a sufficient way. Digitalisation is therefore the fifth factor of success.Through innovative developments digitalisation provides the basis for the other factors of success. In addition, it enables the recording of information from the own manufacturing as well as from serial production which permits the establishment of unique know-how in tooling. Therefore it holds great potential to enhance efficiency of production processes as well as an increase in profitability. Furthermore, digitalisation allows tooling companies to commercialise their existing know-how.

The basis for the know-how is smart data which results from an interpretation of collected process and product data in cyber-physical systems. In tooling, the collecting of relevant information requires individual systems as the company specific conditions differ vastly. Apart from a greater effort, this also leads to important advantages. Through the individual systems the sovereignty of data is owned in the tooling company and the systems address the specific problems in a more sufficient way. In tooling there are several uses for smart data. For example, process data from the serial production can be incorporated into the design of future tools. The positions of components and process sequences can be used for adaptation of planning processes in near real-time. Viewers can be used to replace printed construction data. Hereby, the data is always up-to-date and available for every employee at any time. Digitalisation therefore provides the opportunity to increase the transparency of the manufacturing of tools which is the basis for more efficiency.

Automation

The sixth factor of success is automation. In tooling, the proportion of unmanned production is constantly increasing. Driven by an increasing cost pressure and the need for a reproducible quality of individual processes, systems have been developed which have a very high degree of automation. Despite the high investment costs in such systems, more cost-effective production is possible in the long term, as an almost constant utilisation can be implemented. This can be achieved particularly through a chain of machines and processes, such as the integration of an electrode milling machines, a sinking EDM machine and a measuring device combined in one system.

In tooling, there is a high potential particularly in the automation of manual processes. Thus, tooling companies can focus on know-how-intensive processes like engineering and assembly and allow simple, reproducible processes perform automated. The reduction of errors, but also the improved planning of the process lead to positive effects in terms of cost, time and quality throughout the entire tooling process.

Automated processes also free capacities to expertise-intensive work. Processes can run faster, with a higher predictability and regardless of the presence of employees, whereby a considerable increase in utilisation and thus cost reduction is made possible. In addition, the transparency is increased with respect to the process parameters, enabling a systematic process analysis.

Synchronisation

The seventh factor of success if synchronisation. In tooling, typically the master craftsman occupies a crucial position when it comes to planning and steering of processes. These complex master control leads to a lack of transparency and a high human dependence. To break up these structures and to reduce complexity in order processing, it requires planning at the component level supported by digital tools. Only through this so called high-resolution planning, main process sequences can follow a precise timetable with an daily basis through manufacturing and the operating machines can be utilised efficiently. This requires a comprehensive process understanding of the employees, in particular in the work preparation. This high-resolution planning at component level achieves a high level of transparency along the entire ordering process and enables a systematic design of paralysed processes. In addition, it allows the reduction of interfaces within the company and to the value creation partners. This permits to accurately determine and optimise design cycle times.

The next step is the development of an intelligent planning and control system for dynamic control and rescheduling of orders based on near real-time production information. For this purpose, algorithms are used to select, prioritise and evaluate decision alternatives which are illustrated clearly for both employees and decision-makers. This requires special tool components equipped with data processers and sensors that can provide near real-time data for planning.

Working culture

The most important resource of a tooling company is its employees. Employees in tooling companies have very different qualifications, individual capabilities and various fields of work. The motivation of the employees is crucial for their working results. Motivated employees are more likely to exceed the level of performance that is expected from them. They are more efficient, more creative and create results with better quality. Working culture is therefore the eighth factor of success.

For a short period of time, monetary incentives can help to satisfy the employees. On a long perspective, a high level of satisfaction and motivation depends the individual addressing of employees. In this context, important factors are their working environment, their work content and scope as well as a their personal perspective for the following years. In addition, the benefit of their individual work must be displayed at any time. In this context the work-life-balance as a healthy combination of work and leisure is increasing in importance. New technologies in the context of digitalisation will enable an easier and more individual coordination of working and spare time. Therefore digitalisation helps to increase the employees satisfaction on a long perspective.

In future, tooling companies will have to adopt to major changes. Satisfied and motivated employees are crucial to any change process. The importance of the employees will even increase. Against the background of a demographic change, this issue applies in particular to developed countries. Companies from those countries must make a greater effort to keep their employees and to recruit new ones.

Glocalisation

The ninth and last factor of success is the glocalisation. Internationalisation of business activities is forcing tooling companies to shift their production capacity to different locations. To supply international production sites and to utilise lower factor costs, global markets are increasingly becoming the focus. The aim of the companies is to address the local needs in a better way as well as to utilise cost advantages. However, the utilisation of international markets potentials poses difficulties: Often there is a lack of specific market knowledge of the local tooling industry, making a valid bid comparison or the selection of suitable value creation partners more difficult. Obtaining a comprehensive market intelligence is therefore a decisive competitive advantage.

Market intelligence requires a systematic capture and an intelligent processing of information. In the first step, company specific requirements need to be defined. Afterwards the collection of specific information is followed by its evaluation. On-site audits can be utilised to extend and validate the data collected. The final step is the utilisation and storing of information. This continuous process enables the establishment of market intelligence and therefore an extensive understanding of markets. In these markets, strategic partnerships may be closed. This allows new business models that are tailored to the individual market.

The basic prerequisite for this is a decentralised management of international markets in order to guarantee a short-term responsiveness. Through glocalisation, tooling companies are capable to understand regional cultures and customer requirements and to achieve increased awareness and acceptance in new markets.

3.2 Discussion of the approach

In their practical organisation and implementation, all factors of success are closely interconnected. Instructions for addressing the factors would be insufficient as company specific interests as well as restrictions require an individual approach. Instead tooling companies have to identify the factors of success which are relevant to them. After that they have to exclusively focus on those factors.

With these nine factors of success, tooling companies are able to set a course for success, and control their value creation process more efficiently. The Fast Forward Tooling-approach shows how to respond to current trends and challenges in tooling, and how to achieve success in the coming years. However, the factors of success should not be understood as final objectives. Change and transformation will continue to be constant in the future which must be taken into consideration.

4 CONCLUSIONS

Located between product development and serial production the tooling industry is claiming a key role within the value chain of industrial produced goods. As especially high wage countries have to cope with rising international competition, the improvement of the internal processes and the increase of efficiency have high potential to preserve international competitiveness. Traditionally hand-crafted tooling companies are required to industrialise as the they are not able to compete with their existing structures.

To cope with the challenges of the complex, constantly transforming environment, industrialised tooling companies must take further steps. The Fast Forward Tooling-approach is a new holistic approach tailored for the tooling industry to support the companies for the necessary adoptions. The addressing of the approaches factors of success enables tooling companies to improve their performance and consequently stay competitive in a turbulent environment.

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Selection of Competitive Manufacturing Resources in Tooling Based on Manufacturing Concepts

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Abstract
Tooling companies are challenged today by two major developments: global tooling markets and derivatization. These trends enhance the cost pressure of tooling companies continuously. Due to high manufacturing requirements and high costs of associated manufacturing resources for tooling companies it is necessary to focus on these items. Despite of their importance selection processes of manufacturing resources are mostly done on an intuitive basis today. This can result in low manufacturing competitiveness and capital intense unprofitable investments. In contrast to series production there is currently no tooling related academic methodology available that takes technological and economical aspects during the resource selection process into account. Thus this paper introduces a specific and holistic approach for the selection of competitive manufacturing resources in tooling that is completely based on key figures. The presented methodology consists of two steps. The first step is the derivation of a company specific manufacturing concept. In the next step the included machines are detailed. For the derivation of manufacturing concepts a typology is developed in order to consider the technology variety inside a company as well as the resource utilization. Each of the developed concepts contains the chosen manufacturing technology, the number and size of machines as well as the maximum load and the necessary accuracy. To ensure a maximum of objectivity the selection of a manufacturing concept is based on a utility value analysis in combination with a consideration of the necessary investments so that the selection is realized in the area of conflict between utility and costs. The chosen concept is then an input for the next step of the methodology where all contained machines are detailed in terms of manufacturing relevant aspects. For this key figures are used that are derived by an analysis of workpieces that are machined by the company.

Keywords
Manufacturing Concepts, Resource Selection and Detailing, Tooling, Key Figures

1 INTRODUCTION

The tool and die making industry faces a fundamental structural change. This change is mainly caused by two game changing trends namely globalization and derivatization [1]. In addition to effective process and production planning and control, it is a necessary requirement to adapt the capital intense manufacturing resources to the specific workpiece requirements. Such an adoption ensures a high capability in manufacturing to create superior products under consideration of an efficient cost structure.

Technological resources in tooling have heavily changed over the years. Due to technological progress there are countless feasible manufacturing technologies and corresponding resources that enable a flexible and productive manufacturing in the future [2]. Next to common manufacturing technologies in tooling, e.g. milling, grinding, S-EDM, the application of new and innovative manufacturing e.g. additive manufacturing increases [3]. The technological degree of freedom is furthermore enhanced by developments within the common manufacturing technologies e.g. high speed cutting, five axes manufacturing and so on. A machine tool selection is an important process for many manufacturing companies. Improperly chosen machines can have a negative effect on the overall performance of a production system. [4] Despite of the high relevance of manufacturing resources in terms of competiveness and cost structure there is no systematic selection process for sustainable investment in manufacturing resources available at the moment [5]. Today resources are selected on the basis of an unstructured decision process that contains many intuitive decisions. [2] Those intuitive decisions are unsuitable and should be avoided in the resource selection process, because these can result in capital intense misinvestments.

On that score in this paper a specific and holistic approach for the selection of competitive manufacturing resources in tooling is developed. The procedure is completely based on key figures and it focuses on the resource selection based on an analysis phase and a technology selection process. In the beginning, the initial situation and the requirements for the holistic model are introduced in general (c.f. chapter 2). After that the two steps of the methodology for resource selection are presented in detail (c.f. ch. 3). The first step is to focus more closely on the manufacturing concept (3.1). This includes the basics (3.1.1), the procedure for the determination of a manufacturing concept (3.1.2) and the procedure for the selection of a manufacturing concept (3.1.3). In the second step, the detailing of resources is considered. In chapter 3.2.1 the basics of the resource detailing are introduced. After that descriptions of the mandatory resource components (3.2.2) and the optional resource components (3.2.3) follow. Finally, an example of resource detailing, exemplified by a 5-Axes-HSC milling machine, follows (3.2.4). Chapter 4 completes the paper with a short conclusion.

2 INITIAL SITUATION AND REQUIREMENTS

In the following chapter the current situation and the requirements of the resource selection process are presented. In this context the manufacturing requirement profile (2.1) and the manufacturing capability profile (2.2) represent the technological basis. In combination with a business analysis (2.3) it is possible to realize a final technology selection (2.4) which is a fundamental precondition for the resource selection process.

2.1 Manufacturing requirement profile

The definition of a manufacturing requirement profile is necessary for the resource selection, because of a high divergence and heterogeneity of the workpiece range in different tool and die making companies. From this vantage point, the goal is to get a clear picture of the workpiece characteristics (Y_X). For this purpose the following characteristics are collected [2]:

- (Y_{01}) - Volume change [mm³]
- (Y_{02}) - Max. dimensions [mm]
- (Y_{03}) - Aspect ratio [-]
- (Y_{04}) - Workpiece weight [kg]
- (Y_{05}) - Geometrical characteristics [-]
- (Y_{06}) - Contour radius [mm]
- (Y_{07}) - Dimensional tolerance [µm]
- (Y_{08}) - Parallelism [µm]
- (Y_{09}) - Rotational symmetry [-]
- (Y_{10}) - Surface quality [µm]
- (Y_{11}) - Surface characteristics [-]
- (Y_{12}) - Material hardness [HRC]
- (Y_{13}) - Electrical conductivity [S/m]

A complete investigation of all determinable workpiece characteristics is not necessary to get the proper degree of accuracy [6]. Rather, it is important to describe the geometrical and the material specific characteristics in an adequate way to deduce the manufacturing requirement profile.

2.2 Manufacturing capability profile

Parallel to the manufacturing requirement profile it is important to analyse the manufacturing capability profile. Major point is to find out the limits of specific manufacturing technologies. Therefore, the process related capability and the technological capability need to be examined closer. The following figure shows the different dimensions of the process related capability [2]:

Time	Quality	Costs
Main time	Process stability	Technology cost rate
Setup and Nonmachining Time	Innovativeness	
	Resource efficiency	

Figure 1 - Dimensions of the process related capability

The process related capability describes in consideration of different use cases the economic aspects of the different manufacturing technologies on the basis of three criteria: time, quality and costs. On the other hand the technological side of the requirement profile is realized by analysing the technological capability (L_{tx}). It is foreseeable that the resource and the technology selection in a key figure based selection process have to be designed in the field of tension between workpiece characteristics and technological capability. To synchronize workpiece characteristics and technological capability it is necessary to investigate the technological conflict area in the same dimensions of the manufacturing requirement profile. The determination of the technological capability is done company-specific on the basis of implanted manufacturing technologies. The subsequent figure shows schematically the procedure for the analysis of the technological capability.

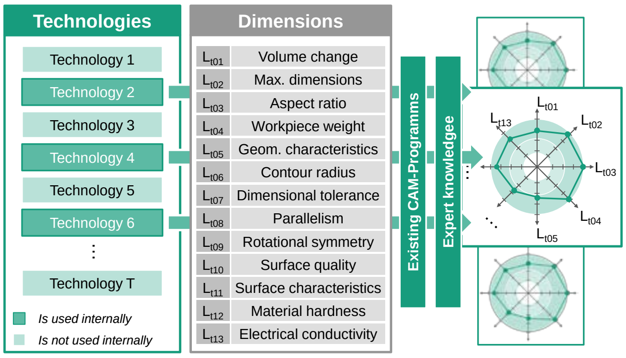

Figure 2 - Analysis of the technological capability

In addition to the collected data it is important to incorporate the expert knowledge of the toolmakers, because often the technology knowledge already exists in the company and should be used. On this baseline the manufacturing capability profile can be determined.

2.3 Business analysis

After considering the technological side of the selection process chapter 2.3 focuses on the economic analysis. There are five important goals for a tooling company to secure the future viability:

quality, time-to-market, productivity, flexibility and innovation [7]. These points relate to the process related capability and must be analysed and adjusted to their suitability for the tool and die making processes. After determination of the target figures a pear-by-pear comparison for target weighting follows [8]. The determined target weights are also the basis for the estimation of technological capacity especially for the calculation of the technology or machine hours.

2.4 Technology selection

The technology selection has a direct effect on the resource selection. As noted above, workpiece requirements and the technological capability, have to be synchronized. This circumstance is shown in the subsequent figure [2].

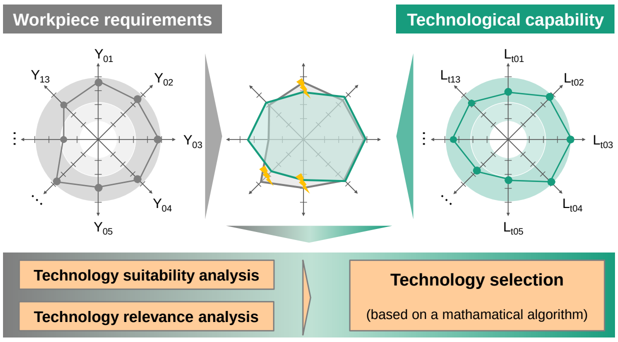

Figure 3 - Interdependency between requirements and capabilities

It is not necessary to discuss the procedure of technology selection in full detail; but some observations must be made. The technology selection consists of two main steps, which are largely generated by a mathematical algorithm. The first step is the procedure for technology suitability analysis. By using a requirement matrix in combination with a capability matrix the algorithm generates a technology feasibility matrix, which includes provisional technology bundles [2]. Building on this, the second step incorporates the procedure for technology relevance analysis in which the provisional technology bundles are refined into final technology bundles with the aid of the process related capability matrix. After generating the final technology bundles it is necessary to carry out a transition from the workpiece perspective to a company perspective. This transition can be realised by an accumulated treatment. The agglomeration shows how often a manufacturing technology is used in the investigated workpiece range. Thus, the result of the technology relevance analysis is an overview of those manufacturing technologies that are necessary under economic and technological aspects for the manufacturing of the required workpieces.

It should be stated at this point that the following aspects are not considered in the technology selection process:

- Substitution of a manufacturing technology by another manufacturing technology
- Substitution via external processing
- Consideration of the resource utilization of the tooling machines

These facts demonstrate that a technology selection has to be followed by a resource selection to increase the level of detail and the precision of the selection process [2].

3 ITEMIZATION OF RESOURCE SELECTION

After introducing the basic requirements for resource selection the subsequent chapter shows the process of resource selection in detail. The first step is the definition of a manufacturing concept (3.1). In connection with that the resource concept has to be specified (3.2). The central objective of this chapter is the selection of specific manufacturing resources.

3.1 Manufacturing concept

3.1.1 Basics

First of all a typologization of the manufactung concept in tool and die making must be invented on the basis of empirical data [2]. The different types should be characterized by a high internal homogeneity but also a high external heterogeneity, so that a clear distinction is possible [9]. The tool and die making sector is characterised by a large workpiece range and divergent business models [10]. These aspects must be taken into account, because they have a direct influence on the resource selection. Key factors for the design of the manufacturing concept are the resource utilization, which is represented by the “Degree of Machining Time (DMT)”, and the “Technological Diversity (TD)” [2] [7]. The classification of these key factors into low and high enables the generation of a portfolio consisting of four fields that are used for the typologization. Figure 4 shows this portfolio:

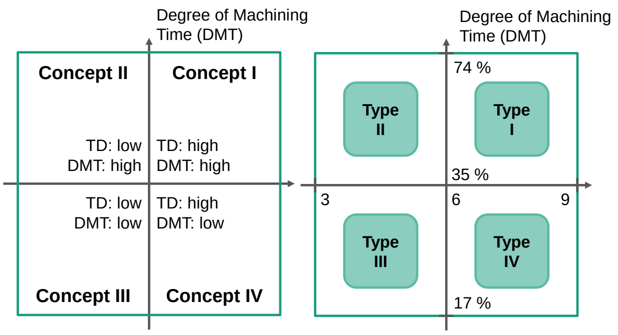

Figure 4 - Ideal characteristics and quantifiable types

The degree of machining time (DMT) is defined as the ratio of the average machining time and the annual disposable machining hours [7]. The technical diversity (TD) is presented on a scale consisting of absolute values. The classification of both variables is reaslised by using threshold values which are generated with the help of a database [11]. The threshold values are the median values of this data base and shown in figure 4 on the right side.

After the definition of classes of manufacturing concepts it is necessary to create a valuation basis to ensure an objective selection process. The subsequent list gives a review of evaluation parameters for manufacturing concepts [2] [6] [12]:

- Productivity
- Flexibility
- Quality
- Automation potential
- Space requirement
- Redundancy
- Reaction speed
- Coordination effect

These aspects were collected with the help of key figures and by the conduction of expert interviews.

3.1.2 Procedure for manufacturing concept determination

The first step of the definition of the manufacturing concept is the calculation of the theoretically necessary number of manufacturing machines. The business analysis is used as the underlying data for these calculations (cf. 2.3). With the help of the number of workpieces, needed technology hours and the different types of workpieces it is possible to determine a capacity for manufacturing resources per observation period. [2] The next step is the determination of the applicable technologies per manufacturing concept. The input factor for this operation is the technology relevance analysis (cf. 2.4). As previously said it is possible that some manufacturing technologies are redundant with regard to their technological capabilty and can consequently substitute each other. This is especially important for dimensioning milling processes. Furthermore a substituition is used by the concepts I and IV to achieve a high technological diversity [2].In addition to the working accuracy it is also important to have a look at the maximum table load of the manufacturing machines.

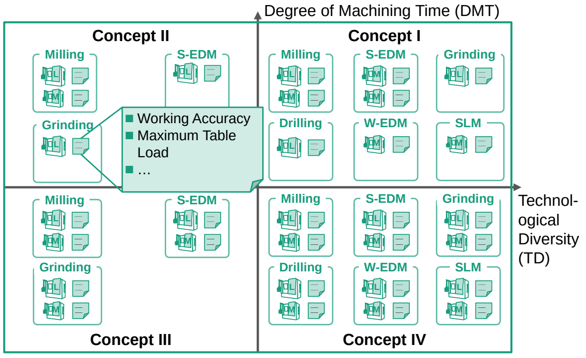

Figure 5 - Exemplified manufacturing concepts

To ensure the practical aplicability, the manufacturing machines and also the workpieces are classified in four groups of length: S (< 400 mm), M (401-600 mm); L (601-1000 mm) and XL (> 1000 mm). Thereby the weight is correlated with the dimension of the workpieces. A large machine can substitute a small one along with higher production costs. However small machines are advantageous in general because of economic reasons. The working accuracy is dedicated to the machines in the same way as the table weight. It must be taken into acount that the investment costs increase exponentially with the working accuracy. Figure 5 shows some exemplified manufacturing concepts.[2]

3.1.3 Procedure for manufacturing concept selection

After the determination of the manufacturing concept the next step is to choose the appropriate concept for the respective tooling company. The subsequent figure shows schematically the procedure for analyzing the utility of the different concepts. [2]

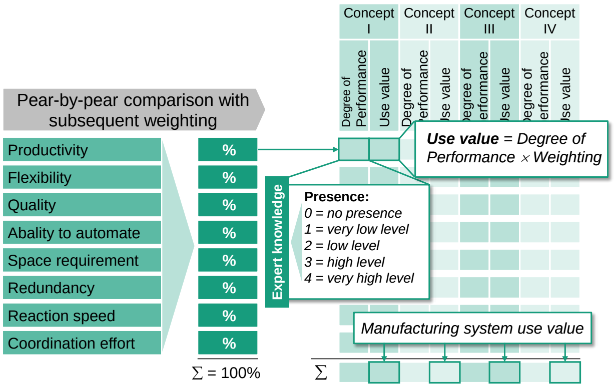

Figure 6 - Utility analysis of manufacturing concept

On the basis of the evaluation criteria mentioned above (cf. 3.1.1) a manufacturing system use value of each concept must be calculated. This use value is calculated by the multiplication of the “degree of performance” and a weighting factor. The degree of performance is determined by expert surveys and the weighting factor is detected by a pear-by-pear comparison [8]. The accumulation over all criteria results in the manufacturing system use value. The concept with the highest use value is seltected and worked out in detail with regard to manufacturing resources [2].

3.2 Resource detailing

After the selection of a manufacturing concept the resource detailing follows. In this case basic relvant machine components (3.2.1) and mandatory resource components (3.2.2) are considered more closely. In chapter 3.2.3 the optional components are introduced shortly before an example closes the detailing process (3.2.4).

3.2.1 Basics

The resource detailing needs a component restriction because of the high number and diversity of machining components [7] [12]. The subsequent figure shows the machine components in the core technologies of tooling, which are collected in a study with the best tooling companies in Germany [13]. Upside in the picture multi-process components are listed and downside the technology specific resource factors are mentioned. These factors are the basis for the further examination. [2]

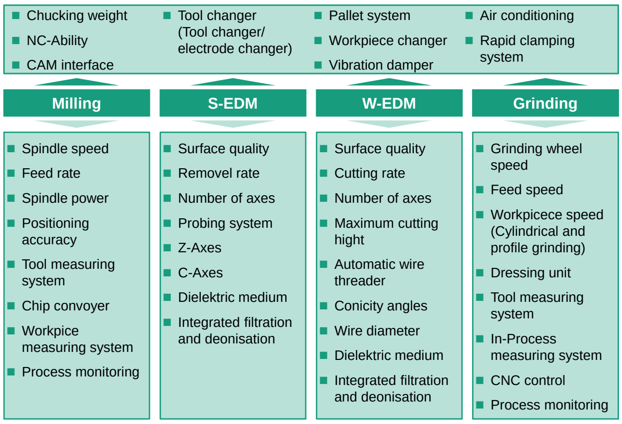

Figure 7 - Focus of resource detailing

3.2.2 Mandatory resource components

The selection of the mandatory resource components depends very much on the manufacturing technology. The procedure is introduced by the example of milling for the sake of simplicity. The working accuracy and the kinematics of a milling machine are the most important factors, which have a direct influence on the productivity. Productivity is an essential criterion for the industrial tooling production and therefore the kinematics are mandatory [1]. Kinematics can be described with the help of the “spindle speed”, the “feed rate” and the “nominal spindle power”, which define the performance of the milling machine. Furthermore the “NC- ability”, a “CAM interface”, “tool changer” and a “tool measuring system” are mandatory resource components, which have a significant influence on the productivity. These aspects are shown in the subsequent figure and were also collected in a study with the best tooling companies in Germany. [13]

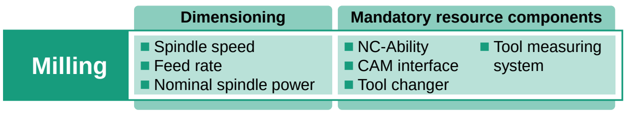

Figure 8 - Mandatory resource components in milling

3.2.3 Optional resource components

In addition to the mandatory resource components, there are also optional components, which have only an indirect influence on the productivity, but a strong impact on the quality of the workpieces and the stability of the process. [2] As examples the following components can be named: Air conditioning, vibration damping system, workpiece and tool measurement system and workpiece changer. Depending on the considered manufacturing technology alternative components can be appropriated. These components are not necessarily needed for the process, but they improve the manufacturing results. The necessity of the use of the optional elements cannot be determined based on quantitative key figures, because the selection is company-specific and not derivable from the fundamental paradigm of the industrial tooling concept. [2]

3.2.4 Example: Resource detailing

For clarification, in the following subsection a resource detailing for a “5-Axes-HSC” milling machine is exemplified including mandatory and optional resource components. The spefic technical data are listed in the subsequent figure:

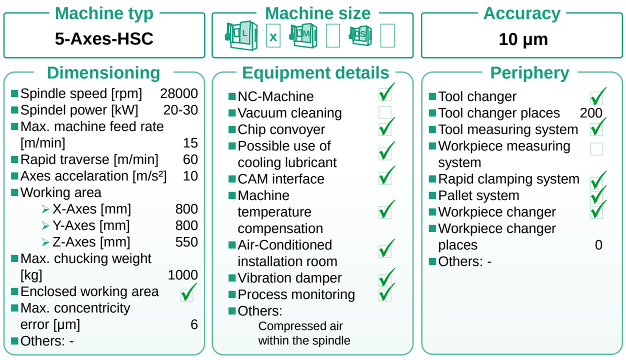

Figure 9 - Part of resource detailing - machine configuration

In this case, the milling machine is dimensioned as type L (cf. 3.2.1). On the left side of the table dimensioning aspects are listed, e.g. “spindle speed = 28000 rpm”. The mandatory and the optional resource components are divided in “equipment details” and “periphery”. Representations in the analogous form should be made for the other manufacturing resources implemented in a specific manufacturing concept.

4 CONCLUSIONS

The procedure for “selection of competitive manufacturing resources in tooling” has been introduced along methodically developed steps. After presenting the initial situation and the introduction of the manufacturing requirement profile (2.1), the manufacturing capability profile (2.2) the business analysis (2.3) and technology selection (2.4), in chapter 3 the resource selection is itemized. The first step within the manufacturing resource selection process is the selection of company-specific manufacturing concepts, which are evaluated on the basis of a defined evaluation process. After the selection of the final concept, a further resource detailing of machining and resource components follows. Nearly the complete selection process is based on key figures, which enables an objective assessment. This procedure provides a specific and holistic approach for the selection of manufacturing technologies and especially manufacturing resources in tooling. This approach is suitable for tooling companies and (with minor adaptions) for companies in the field of small scale productions. [2] This in turn provides a relevant contribution for the competitiveness of tooling companies in high wage countries.

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6 BIOGRAPHY

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Evaluation of Surface Texture Assessment of Titanium Dental Implants

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Abstract

Competitive manufacturing implies, amongst others, appropriate evaluation of fit for purpose manufacture and finishing of parts. Titanium dental implants generally possess modified, treated, and/or coated surfaces for the purpose of improved implant-to-body interface performance. Consider that the body elements that interact with a newly inserted implant range between 6 µm and 80 µm in diameter; it is asserted that topography and texture at those length scales influence the biomechanical performance of the implant. The main topic of the research is the evaluation of surface texture resulting from the manufacturing process. Conventional surface roughness evaluation techniques may not be appropriate for effective topography assessment of dental implants. Surface texture evaluation at these reduced length scales is uncommon and not yet clearly defined. The problem of analysis and quantification of the surface texture was apparent when the current established evaluation techniques were applied; e.g. a standard cut-off filter length of 0.8 mm (800 µm) is typically used. Measurements of dental implant roughness made with this cut-off length were therefore deemed inappropriate. The focus of the research was to establish a standard set of evaluation parameters that are suitable for the measurement of dental implant surface texture. The filter cut-off length, resolution, and sampling frequency significantly influenced the output texture descriptors. Limitations of conventional roughness measurement equipment (profilometer) were encountered with respect to the maximum capture resolutions in areal analysis, and to the complex geometry of the screw type dental implant. SEM was used as a tool for the capture of the surface information. The desired parameters for the evaluation of dental implant surfaces used in the SEM were concluded to function correctly, and be appropriate at the body element length scale.

Keywords

Dental implants, Osseointegration, SEM, Surface texture, Titanium Grade 4.

1 INTRODUCTION

Commercially pure titanium is a popular material for use in dental implants due to the combination of mechanical properties and excellent biocompatibility it offers. Dental implant performance may be measured in a variety of ways, however a common metric is the level of bone contact to the implant surface after a set amount of time. Osseointegration has been formally described in the literature as the structural and functional connection between living bone and a load carrying implant [1]. A number of factors influence osseointegration performance, of which surface topography was one of the explicitly identified factors [2]. The effects of surface roughness on dental implant performance has been the subject of investigations in the past; where consensus over the ideal dental implant surface roughness has yet to be reached. The currently accepted range of suitable arithmetic mean roughness, R_a, for dental implants is expressed in Eq. 1 [3].

$$1.0\,\mu m < R_a < 1.5\,\mu m \qquad (1)$$

Adding to the uncertainty is the issue where most published articles relating to titanium dental implant surface roughness do not supply the acquisition information necessary to systematically reproduce the measured surface roughness results [4]. As an example, the filter cut-off length used in primary profile filtering can take on many values, but the 'default' is 0.8 mm. If it is understood that default acquisition parameter values apply in published research articles for the cases where insufficient acquisition information was explicitly stated, then the accepted and recommended R_a values would range between 0.01 µm to 1.5 µm. The lower bound of this 'default' range is two orders of magnitude lower than that indicated in Eq.1. This observation highlights a possible source of confusion in the fields of research, development, and manufacturing of titanium dental implants.

More recent research has moved beyond general surface roughness and on to investigating specific surface texturing at nanometre length scales [5, 6]. It is noted that some of the research suggests nanometre texturing optimises and enhances dental implant performance. The fact that the generally accepted roughness range of a dental implant is at the micrometre length scale when recent research points to influences at the nanometre length scale, suggests that surface roughness should in fact be measured at further reduced length scales.

2 ROUGHNESS EVALUATION

2.1 Previously used texture descriptors

A review was conducted where 57 recent papers, all specifically focussed on titanium dental implant surface evaluation, were interrogated with regards to the texture descriptors utilized for dental implant surface description. Four texture descriptor categories were identified from the publications: amplitude, functional, hybrid, and spacing descriptors. Amplitude descriptors were the overwhelmingly popular descriptor category stated in the reviewed publications (see Figure 1) [4]. The most common amplitude descriptor, and in fact general descriptor, quoted in the evaluation of titanium dental implant surface texture is that of the arithmetic mean roughness, R_a and/or S_a [4].

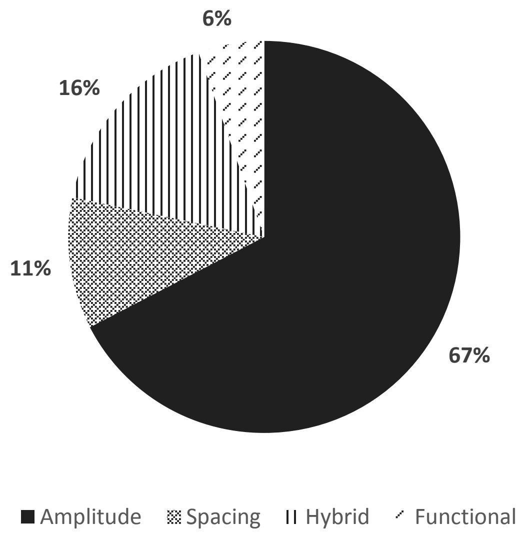

Figure 1 - Comparison of roughness descriptor occurrences by category in published journal articles directly related to the surface texture of titanium dental implants

2.2 Evaluation parameters

Every roughness measurement that yields a roughness descriptor value possesses a set of evaluation parameters that are implicit in the measurement and the calculation of the associated numerical value. Evaluation parameters involved in the standard practice of roughness measurement include:

1. Evaluation standard/s;
2. filter cut-off length, (λ_c);
3. filter size, (λ_s);
4. evaluation length/area, (L_s); and
5. resolution, (λ_r).

The property of length influences all of the listed evaluation parameters. Most of the evaluation standards offer guidelines based on the desired evaluation length, where combinations of evaluation parameter settings are described as per evaluation length. λ_c, λ_s, and L_s are explicitly dependent on length, whereas the dependence of λ_r is not as immediately apparent.

2.2.1 Length scale range

It is put forward that the body's cells and tissues interact with the implant surface; hence it is suggested that roughness measurement length scales should be selected accordingly. It is assumed that the osseointegration process starts soon after the implant is inserted into the bone, during a process referred to as wound healing. Three stages were identified in the bone response during wound healing along with the tissues involved; the information is presented in Table 1.

Stage	Event	Tissues
Osteo-conduction	Hematoma formation and mesenchymal tissue development.	Blood cells, platelets, monocytes.
Bone formation	Woven bone formation.	Osteogenic cells (differentiate into osteoid tissue).
Bone remodelling	Lamellar bone formation.	Trabecular bone developed from osteoid tissue (Osseointegration).

Table 1 - Brief view of skeletal response to implant induced injury for a cementless implant [2, 7]

A list of the typical cells and tissues involved in the wound healing process is presented in Table 2 with their associated diameters. Since lymphocytes are involved in the immune response, the lymphocyte diameter was selected as a minimum length for roughness evaluation. The maximum length for roughness evaluation was selected based on the largest diameter of a macrophage. The proposed length scale range for measurement is expressed in Eq. 2.

$$6\ \mu m \leq \text{Range} \leq 80\ \mu m \quad (2)$$

Body cell/tissue	Cell diameter [μm]
Red cell (blood)	$\sim 3 < \emptyset_{rbc} < \sim 8$
Lymphocytes	$\sim 6 < \emptyset_{lmc} < \sim 12$
Fibroblasts	$\sim 10 < \emptyset_{fib} < \sim 15$
Osteocytes	$\sim 10 < \emptyset_{ost} < \sim 20$
Macrophages	$\sim 20 < \emptyset_{mac} < \sim 80$

Table 2 - List of cells associated with bone growth and their cell diameters [8]

Throughout the literature related specifically to surface texture analysis of titanium dental implants, a limited number articles have stated the complete measurement parameters used in the determination of the stated surface roughness descriptors [4].

3 MATERIALS AND METHOD

3.1 Dental implants

A commercially pure grade 4 titanium (cpTi Gr-4) titanium dental implant and cylinder were subject to surface texture evaluation. The implants had a maximum diameter of 6 mm, minimum diameter of 4 mm, and a length of 12 mm. The reference cylinder with similar surface treatment had a dimeter of 5 mm and a length of 15 mm.

Figure 2 - Titanium dental implants and cylinder

3.2 Surface treatments

The surfaces of the titanium dental implants and the cylinder were treated by a grit blasting process using alumina particles. The blasting conditions were 3 cm/min at 35 psi. It is noted that the cylinder surface had undergone similar modifications to those of the titanium dental implants and was isotropic in its surface texture [4]. Both the implants and the cylinder were provided by Southern Implants.

3.3 Surface roughness and topography

A 2D contact stylus profilometer (Hommel-Etamic T8000) and scanning electron microscope (SEM) (Tescan Vega3 LM) were used for the texture evaluation of the surfaces. It is noted that use of the profilometer was limited in the case of the dental implant due to the implant's complex geometry and the mechanics of operation of the stylus trace measurement. The sets of surface information acquired from the profilometer and SEM were combined in order to measure the surface texture of the implant threads.

Customised code was written in order to facilitate the combination of profilometer and SEM image data. Raw data acquired from both instruments was subject to ISO 11562 filtering, and the use of a phase correct 1D/2D Gaussian filter was used to separate the waviness profiles from the primary profiles.

3.4 Methodology

The evaluation parameters of filter cut-off length (λ_c), filter size (λ_s), and sampling resolution (λ_r) were investigated for their influence on output roughness descriptors. Each parameter was individually varied while the other measurement parameters were kept constant. An extracted profile from the cylinder surface was used as a base to investigate the measurement parameter effects. Surface roughness evaluation of the cylinder was conducted using the profilometer with the following conditions: a trace length of 12 mm, a trace speed of 0.15 mm/s, and ISO 11562 filtering. A set of 'allowable' evaluation parameter conditions was then determined using the results.

The surface of the dental implant, particularly the threads, was then examined using SEM. It is noted that single image SEM has generally been used qualitatively, and that for quantitative analyses stereo-SEM has often been required. A technique was developed that allowed the use of a single SEM image to be converted into surface height information, which effectively was a conversion into a topographic map of the scanned surface. The dental implant thread surfaces were then evaluated in terms of the determined 'allowable' measurement parameters.

4 RESULTS AND DISCUSSION

4.1 Length scale evaluation

4.1.1 Influence of varied evaluation parameter magnitudes

The effects of varied magnitudes of λ_c, λ_s, and λ_r on output roughness descriptors were briefly studied using a profile measured from a titanium cylinder of constant diameter and with isotropic surface texture. The results of varying parameter values on the output roughness descriptors are presented in Figure 3, Figure 4, and Figure 5. These results are applicable only with the measurement parameters supplied. Since the suggested body cell imposed length scale ranges between 6 µm and 80 µm, the results will be analysed in context of that length scale range.

The results of the filter cut-off length on the selected roughness descriptors are presented in Figure 3. It is apparent that R_a varies between 0.1 µm and 0.9 µm depending on the filter cut-off length used. The range influenced most by filter cut-off length appears to be between 1 µm and 2000 µm – the body cell range, therefore, appears to be within the region of greatest influence of the filter cut-off length parameter. For filter cut-off lengths larger than 2000 µm the influence diminishes. It is noted that at extended filter cut-off lengths the influence on output roughness descriptor values further diminishes; an observation that can be linked to the cut-off length exceeding the filter size.

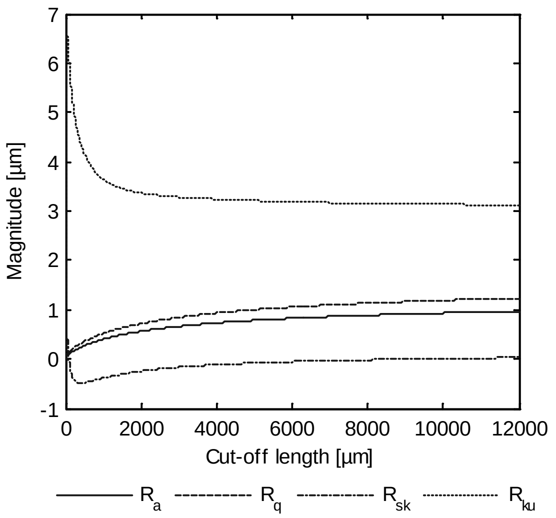

Figure 3 - Profile parameters for variable cut-off lengths, λ_c, for constant λ_s (2400 µm) and λ_r (0.5 µm)

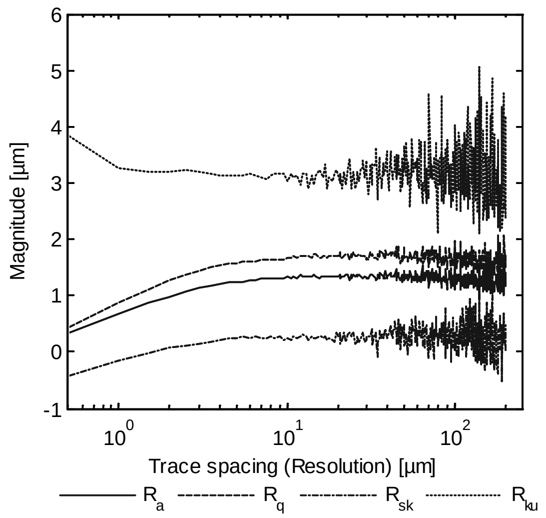

Figure 4 - Profile parameters for variable trace spacing, λ_r, for constant λ_c (0.8 mm) and λ_s (2400 µm)

The results of the filter trace spacing (effectively the filtering resolution) on the selected roughness descriptors are presented in Figure 4. It is recognised that at a sampling spacing of one, the resolution is at its maximum. It is assumed that this resolution contains the most surface information, and therefore should present the most accurate roughness descriptor results. The deviations in all of the indicated roughness descriptors for spacing values larger than one are therefore representative of the error between the true values and the subsequent resulting values due to a loss of surface information. It is observed from the plots that all the roughness descriptors tended relatively smoothly towards constant values for sample spacing in the range between one and twenty, after which the roughness descriptor values became unstable and oscillated around the mean (relatively constant) trends.

The implication of these observations is that due consideration should be given to the measurement resolution offered by the instrument. In the context of the results presented in Figure 4 and that of the body cell lengths, it is recognised that only the maximum (or near maximum) resolution offered will provide sufficient information to characterise the surface texture for the smallest cell diameter (6 µm). The use of the larger body cell diameters as constraints therefore would offer greater flexibility in the acquisition of surface texture information.

The results of the filter lengths on the selected roughness descriptors are presented in Figure 5. It appears that filter length influences the output descriptor values up to approximately 0.5 mm, after which the roughness descriptor results tend to constant values with minor oscillations around the mean trend lines.

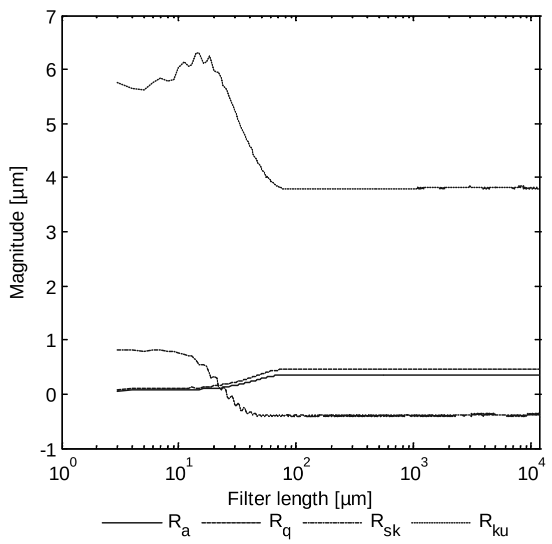

Figure 5 - Profile parameters for variable filter length, λ_s, for constant λ_c (0.8 mm) and λ_r (0.5 µm)

4.1.2 Evaluation parameter magnitudes

A set of evaluation parameter values suited to dental implant surface texture analysis may be proposed. With consideration to the body cell length scale range, and the results presented from the investigation into the effects of evaluation parameters on output roughness descriptors, a list of acceptable evaluation parameters and their magnitudes is presented in Table 3. The expressed evaluation parameters values were applied to evaluate the surface roughness of an actual dental implant thread (flank).

Evaluation parameter	**Acceptable range**	**Selected value**
Body cell/tissue diameters [μm]	$\sim 6 < \emptyset_{BC} < \sim 80$	80
Filter cut-off length, λ_c [μm]	$1 < \lambda_c < 2000$	80
Filter size, λ_s [μm]	$\lambda_s > 100$	160
Sampling resolution, λ_r [μm]	$\lambda_r < 1$	0.978

Table 3 - Selected evaluation parameters for dental implant surface texture evaluation

4.2 Evaluation of dental implant thread

A capture of one side of the dental implant is presented in Figure 6 where implant geometric features are clearly distinguishable. Roughness evaluation of the implant thread surfaces using the evaluation parameter magnitudes described in Table 3 was performed. The mean results of surface roughness of the evaluation are presented in Table 4, where it is noted that the surface roughness 1.07 µm fits in to the currently accepted recommended roughness range (1.0 µm to 1.5 µm) as described by the literature. While the observation over the difference between the evaluated and recommended roughness values is easily made, consideration should be given to the differences in measurement conditions and parameters used. In the literature it is not clearly stated which measurement parameters apply to the recommended roughness range, therefore direct comparison/reference to the accepted roughness range should be performed with care.

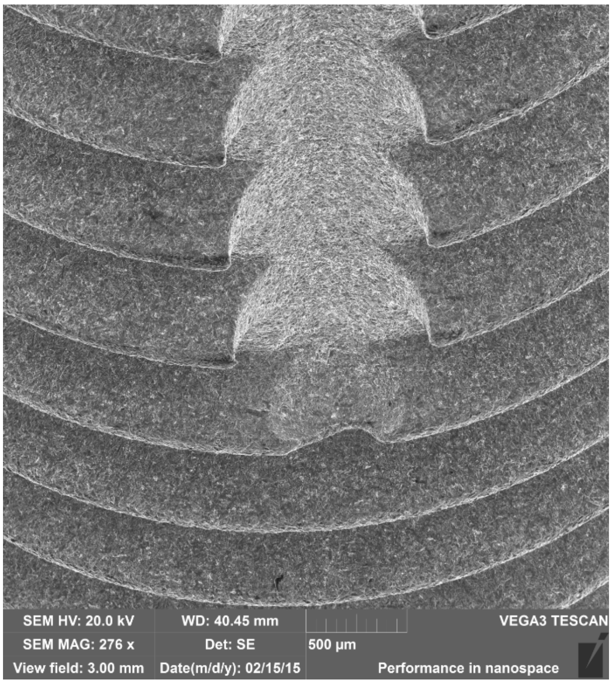

Figure 6 - SEM image of implant tilted 30 degrees in order to expose the thread flank surface

Parameter	**Mean [µm]**
S_a	1.07
S_q	1.84

Table 4 - Surface parameter values for threads where 1st thread is located at the bottom, and the 6th thread is located at the top (λ_c = 0.08 mm, λ_s = 160 µm)

5 CONLCUSION

The influences of surface roughness evaluation parameters on the output roughness descriptor values were investigated with the intention of providing a guide for surface texture evaluation in the context of titanium dental implants. An estimation of allowable magnitudes of these evaluation parameters was made, where body cell diameters, and instrument sampling resolution, were used as constraints. The allowable evaluation parameter magnitudes are:

1. The allowable filter cut-off length, λ_c, ranges between 1 µm and 2000 µm. A filter cut-off length of 80 µm is suggested (constrained by macrophage cell diameter).
2. Filter size, L_s, influences are reduced at larger filter lengths. A filter size twice that of the allowable filter cut-off length is recommended.
3. Sampling resolution, λ_r, significantly influences the magnitude and quality of the roughness descriptors. It is suggested that a minimum number of samples be collected based on the smallest length scale desired. For instance; based on a minimum body cell diameter

(lymphocyte – 6 µm diameter), and using a minimum of 5 samples per filter length, the maximum allowable spacing between data points is 1.2 µm.

The above estimations were used in the evaluation of an actual dental implant's thread flank, the surface information of which was captured using SEM. The mean thread surface roughness was calculated (S_a = 1.07 µm), where comparison to the recommended range of roughness showed that it was within the generally accepted recommended range. Since the measurement parameters were not stated for the recommended range of roughness, however, a direct comparison between the two values should not be performed. Surface roughness descriptors should be accompanied by a set of evaluation parameters used in their acquisition, and that only descriptors supplied with this information may be reliably referred to and used for comparative studies.

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7 BIOGRAPHY

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Surface Engineering of Titanium for Biomedical Applications by Anodizing

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Abstract

Competitive manufacturing implies fit for purpose and efficient manufacturing practices. Dental implants are biomedical parts that are manufactured from either Grade 4 or 5 Titanium alloy. In certain situations it may be beneficial for patient satisfaction purposes and for product identification marking to change the appearance (colour and reflectance) of the implant. In the present study, a TiO_2 based coating is applied on commercially pure titanium (Grade 4) alloy substrates by the anodizing process. The objective of this study was to engineer the aesthetic appearance of the dental implants while monitoring its effect on aspects as regards to biocompatibility and function. Chromaticity (colour and hue) and reflectance are investigated as a function of the anodizing process parameters (electrolyte voltage, current and electrolyte). Grade 4 titanium was anodized in diluted sulphuric acid electrolyte at various voltages. The reflectance of the anodized specimens was measured with a spectrophotometer. Surface roughness, oxide film thickness and chemical composition of the oxide phase were measured. By varying the electrolyte voltage between 5 V to 40 V different colour ranges were produced. It can be concluded that the surface colour of anodized titanium is dependent on the oxide thickness layer thickness and therefore the applied voltage. Conventional surface roughness did not change and was similar to the virgin material. Elevated voltages resulted in a more crystalline oxide layer. The aesthetic appearance of titanium implants may be improved.

Keywords

Titanium grade 4, Anodization, surface roughness, reflective index and TiO_2, TiO_2 thickness and XRD spectra.

1 INTRODUCTION

Titanium and its alloys are attractive because of their high strength to weight ratios, excellent corrosion resistance and fatigue properties. These properties along with its perceived biocompatibility make them especially useful for orthopedic and dental implants. However, titanium is a bioinert material that neither bonds to the bone tissue directly nor induces bone growth as compared with the stainless steel 316L, CrCoMo and calcium phosphate coated implants [1]. Therefore, various surface modification techniques have been developed and applied to titanium implants in an attempt to improve the bioactivity. Titanium falls within the group of neutral biomaterials that does not chemically bond with bone tissue. Because of the improvement in casting techniques of titanium alloys along with progress in CAD/CAM and electric discharge machining there has been renewed interest in the use of titanium and its alloys for fixed and removable prostheses [2]. Titanium has a dark iron like appearance that may be problematic as far as aesthetics are concerned when used in biomedical applications especially if it is exposed or visible in some way. A typical application is in the manufacture of dental implants. An ever increasing demand for dental implants for the restoration of oral functions such as chewing and oral communication and/or the restoration of aesthetic appeal has led to the need for practical and effective ways to improve and maintain the function of implants but also with acceptable aesthetic appeal. Sections or components of the implant assembly may therefore be coloured to improve aesthetic appeal during implant exposure or tissue recession. A coloured collar may for example be inserted on the top of the implant for aesthetic purposes. The surface of this collar may have markedly different requirements than the coronal portion of the implant surface. This surface, albeit coloured, needs to be smooth to reduce dental plaque deposition and to facilitate easy cleaning. Manufacturers and physicians also require simple and effective techniques for product identification marking without having to resort to marking techniques that introduce additional foreign substances into the mouth cavity.

Anodizing is an electrolytic chemical oxidation process whereby the oxide layer thickness is engineered to thereby change the appearance (colour) of titanium. The thin passive oxide layer formed is usually more stable and thicker than the natural occurring oxide layer which is formed in contact with air. The anodic oxidation of the titanium surface for implant application is relatively inexpensive and may produce a uniform thickness throughout the surface area [3]. The anodic oxidation of titanium may also improve the corrosion resistance [4]. The implant corrosion resistance is important because certain specific metal ions released during corrosion can induce a reaction around the implanted surface that may cause fixation failure. The corrosion resistance and biocompatibility of metals are largely the result of a passive oxide layer on the titanium surface [5]. The oxide layer and colouring is directly related to the anodizing voltage. The colours formed on the titanium surface are knows as interference colours. There is no dye associated with the formation of these colours. This study was conducted to investigate the spectral reflectance, chromaticity, refractive index, oxide layer thickness, surface roughness and makeup of the oxide layer on anodized titanium at different voltages.

2 MATERIALS AND METHOD

Grade 4 titanium was used as workpiece material for this study. The samples for anodizing were cut from 2 mm grade 4 titanium plates. The chemical composition is given in the Table 1. The samples were cut to dimensions of 25 mm × 35 mm and then degreased by acetone and acid washed with 40% HNO3 solution for 20 s according to ASTM B600. The samples were then washed twice with distilled water to remove the traces of acid. The samples (surface roughness, Ra = 1.28 µm) were anodized in 20% concentrated sulphuric acid (H2SO4) electrolyte bath for 2 min for various constant voltages using a potentiostat. The anodizing voltage was varied in the range of 5 - 40 V, with incremental step of 5 V. After anodizing the samples were washed twice again with distilled water. The colours (irradiance and reflectance) of the anodized samples were measured with a UV spectrophotometer (Varian model Cary 5000 UV-VIS-NIR) with an observation angle of 20 - 70 degrees. The spectral reflectance was recorded for wavelength's varying between 200 to 2000 nm. The thickness of the anodized layer was determined by noting at what wavelength the maximum % spectral reflectance occurred and then applying equations Eq (1) and (2)[3].

$$t = \frac{\lambda_{\max}}{4n_o} \tag{1}$$

$$n_o^2 = 5.193 + \frac{2.441\times10^7}{\lambda_{\max}^2 - 0.803\times10^7} \tag{2}$$

Where; t is the thickness of the film in nm, λ_{max} is the wave length of maximum film intensity absorption in nm, and no is the film refractive index. Oxide film refractive index varies with wavelength which can be obtained from the Eq (2).

Element	C	N	Fe	H	O	Ti
% by weight	0.010	0.01	0.20	0.002	0.30	Bal

Table 1 - Chemical composition of grade 4 titanium plate

The surface roughness of the anodized samples was measured by using a Hommel surface profilometer (HOMMEL-ETAMIC T8000). The centerline average surface roughness of the samples was measured with 0.8 mm cut off value and 15 mm traverse length. An average surface roughness (arithmetic surface roughness, Ra) was measured at six different locations in both the longitudinal and transverse directions of the anodized surface. The chemical composition of the samples was measured by Energy dispersive spectroscopy (EDS) whereas the crystal structure was determined by X-ray diffraction (XRD) with a thin film collimator (X'pert Pro MRD, Philips ltd, Eindthoven Netherlands).The step size used in the scan was 0.02° over the range of 10° - 90°. The spectra was recorded using Cu Kα radiation (0.154056 Å) generated at an acceleration voltage of 40 KV and a current of 40 mA.

3 RESULTS AND DISCUSSION

3.1 Colour

Table 2 shows the created colours on the titanium during the anodizing at different voltages in diluted sulphuric acid. When the titanium immersed in an electrolyte the current is drawn, the oxygen is generated at the anodic surface and combines with the titanium to form a titanium oxide. This oxide layer thickness increases in relation to the amount of voltage applied with the time. As oxide layer thickness its resistance to the passage of current also increases [3]. For any applied voltage the oxide layer grows and then stops when the resistance has increased to a point where the current is decayed to a value at which only few OH- ions are available to support continued film growth. The colour of the anodized titanium samples at different voltage determined by the naked eye are given in the Table 2. It is generally known that titanium anodize produce an inert transparent oxide film capable to generating interference colours. This is the simplest method and economic, it utilized ordinary chemicals to produce stable oxide with different colours at room temperature within 2min [4]. The produced colours are no pigments or dyes. The interference colours are produced by thin transparent film on a reflective surface. The film has an ability to reflect, refract and observe the light. The white light falling on the film is partially reflected and partially transmitted. The transmitted fraction reaching the metal surface is again partly absorbed but largely reflected back to oxide film. A phase shift occurs during this process together with multiple reflections. The degree of absorption is dependent on the oxide layer thickness. The different thickness of oxide film causes the variations of luminous flux, refractive index and reflective index, produces various specific colours of the anodized titanium. Figure 1 illustrates that when the colours of titanium anodizes at different voltage at 5 to 40V, the spectral reflectance indexes varies specifically. It is determined that the colour and thickness of the oxide is dependent on the voltage applied. Golden yellow colour is obtained at 40 V; it seemed that the colour films are applicable and practically in dental clinic to colorize the titanium dental frameworks of dentures in order to enhance the aesthetic of implants by anodization due to golden yellow colour harmonious with the colour of the teeth. The other colours produced by anodizing may be used for colour coding of the abutments to recognize implanted size and type. Even they probably used in the applications of jewels, with crucial requirements of good reliability of hue on differently finished surfaces.

Voltage (V)	colours
5	Tiny yellow
10	Dark golden
15	Dark brown
20	Purplish blue
25	Shallow blue
30	Sky blue
35	Grayish yellow
40	Yellowish gold

Table 2 - The correlation of colours to volts of anodized titanium

3.2 Refractive index and Thickness

Figure 1 shows the spectral reflectance of each sample obtained by the spectrophotometer. The thickness of the anodic film and the refractive index was calculated from λmax using the Eq (1) and (2). Figure 2 shows the changes in the refractive index versus the anodizing voltage. It can be seen that the increase in the anodizing voltage increases the anodic film thickness which implies a decrease in the refractive index of the layer. This is because of increasing anodizing voltage, the density and compression of the anodic film is decreased [6]. The highest refractive index obtained was 1.457 for the sample at 5 V while the lowest refractive index was 1.421 for the sample at 40 V. Figure 3 presents the variation in film thickness as a function of the anodizing voltage. In essence the anodic film thickness increases linearly with increasing applied voltage for a constant anodizing time. Initially a high current density is realized with the application of the constant voltage that drops quickly almost immediately from its maximum value to then stabilize and eventually to become constant. Once the initial growth has occurred and the color changed the current density reduces dramatically and the film is essentially stable.

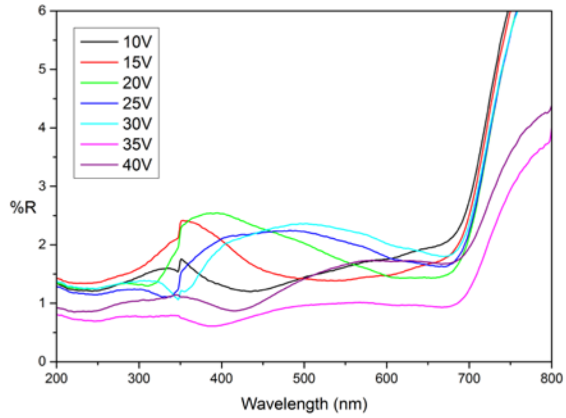

Figure 1 - Reflectance spectra of interference colors obtained as a function of voltage from 10 to 40 V

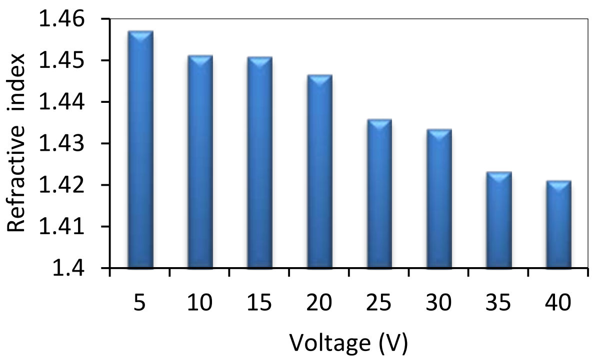

Figure 2 - Changes in the refractive index of anodized samples

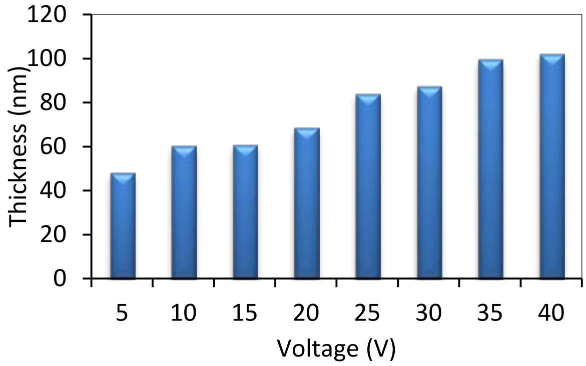

Figure 3 - Changes in thickness of anodized samples Vs. anodizing voltage

3.3 Surface Roughness

Figure 4 shows the surface roughness of the anodized samples at different applied voltages. The data shows that in essence the roughness (Ra) remained constant and is similar to the unanodized virgin sample. This shows that even though there was a change in the color of the surface and growth of the oxide layer there was no changes in the surface roughness after 2 min of anodizing. This conclusion is of course only valid for the length scale considered as applicable to the standard roughness measurement as conducted. At reduced length scales there may be changes in the surface roughness due to the oxide layer growth due to secondary oxide particles [7]. Zhu et al. [8] also considered oxygen (O_2) bubble generation during anodizing of aluminum that result in the formation of a porous surface morphology. O_2 bubble formation may therefore play a significant role in reduced length scale roughness and should be considered for future investigation.

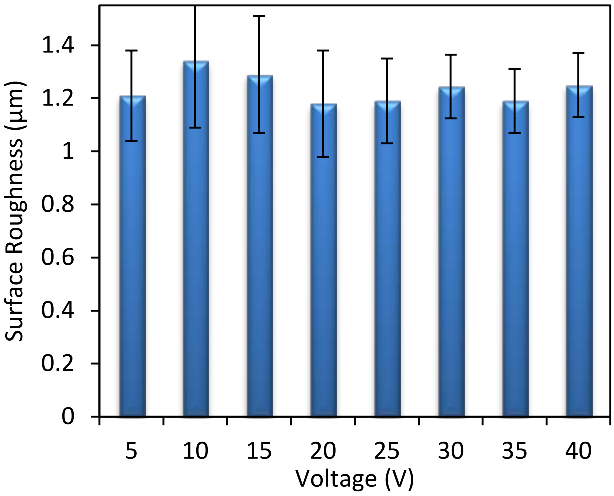

Figure 4 - Effect of Anodizing voltage on surface roughness

3.4 Crystal structure

The XRD pattern shown in Figure 5 reveals the amorphous structure of the oxide films in the anodized sample at an applied voltage of 10 V and 40 V. The oxide film (TiO_2) formed by the diluted sulfuric acid (H_2SO_4) electrolyte forms a rutile structure on the surface of the titanium. As observed from the XRD spectra the intensity of the titanium phase is decreased for higher anodizing voltage (40 V) compared to the low anodizing voltage (10 V). The oxide layer formed for the 40 V anodized sample has a higher TiO_2 content compared to the 10 V anodized sample (see quantitative analysis Table 3). The increased oxide layer may enhance the biocompatibility of the implant with the surrounding tissues and helps to grow the cells at a faster rate[7]. In general, at low voltage the oxide film was amorphous but with increasing voltage the structure of the oxide film may change from amorphous to a crystalline oxide. The crystalline oxide (anatase) of titanium are reported to be beneficial bone growth and response to the surrounding tissues compared to the amorphous structure [9].

Phase name	Content(%) 10 V	Content(%) 40 V
Titanium Oxide	---	26.40
Rutile	0.32	7.02
Titanium	99.68	66.57

Table 3- Quantitative analysis of XRD results

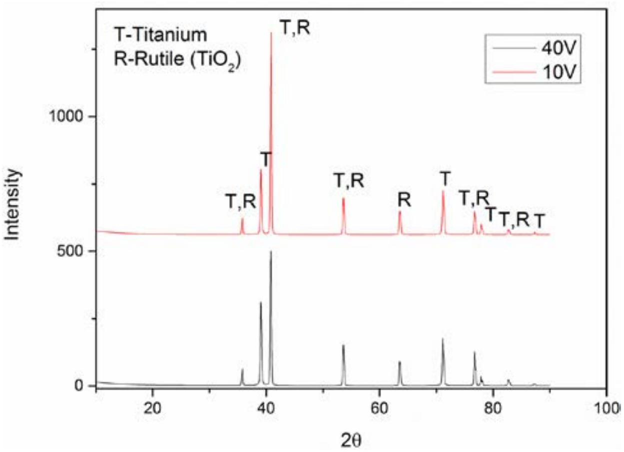

Figure 5 - XRD spectra of anodized sample at 15V and 40 V

4 CONCLUSIONS

1. Titanium Grade 4 was anodized in dilute sulfuric acid electrolyte at various voltages. The following conclusions are drawn.
2. Different interference colors are produced with different voltages. This is similar as demonstrated by various other investigations.
3. The refractive index of the anodic film decreased, which showed that the density of the anodic film has decreased. The thickness of the anodic film increased by increasing the anodizing voltage.
4. The XRD spectra showed that the oxide layer is stable. The crystalline TiO_2 structure that is a characteristic of the higher voltage anodizing may enhance bone growth and better bonding between the surrounding tissues in biomedical implant use.
5. Anodizing did not significantly change conventional surface roughness. The effect on reduced length scale roughness is still unclear and should be investigated in more detail as there is evidence that suggests that the biomedical behavior of titanium implant surfaces may be a function of roughness at different length scales.

5 ACKNOWLEDGMENTS

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7 BIOGRAPHY

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Developing a Patient-Specific Maxillary Implant Using Additive Manufacturing and Design

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Abstract
Maxillectomy is the surgical removal or resection of the maxilla or upper jaw bone. A total or partial maxillectomy can be performed depending on how far the tumour has spread. This paper will discuss a patient diagnosed with an aggressive tumour in half of the top jaw who had to undergo an operation to remove the hemi-maxilla and orbital floor. Due to the extent and complexity of the defect, it was decided to manufacture an anatomical model of the hard tissues for planning a possible laser-sintered titanium implant using Additive Manufacturing (AM). The CRPM had only two weeks to design and manufacture the titanium implant, due to the severity of the tumour. The anatomical model was sent to the surgeon to cut the nylon model where the bone resection was planned. Furthermore, the prosthodontist made a wax model of the planned titanium frame that was reverse- engineered and used as reference geometry in the design software.Materialise® design suite was used to design the patient-specific maxilla and cutting jig. The EOS M280 Direct Metal Laser Sintering (DMLS) system was instrumental in achieving the direct manufacturing of the bio-compatible titanium implant. The EOS P385 system was used to manufacture the pre-operation planning model as well as the cutting jig.The process chain followed to complete this case study will be discussed showing how this intervention improved the quality of life of a SA patient. Furthermore, the proposed paper and presentation will discuss the post-operation review of the patient showing the impact AM had in accelerating patient-specific implant manufacturing. The authors seek to claim a progressed level of maturity in the proposed manufacturing value chain. The claim is based on the successful completion of the analysis and synthesis of the problem , the validated proof-of-concept of the manufacturing process and the in-vivo implementation of the final product.

Keywords
Additive Manufacturing, patient-specific, titanium

1 INTRODUCTION

Amelobastomas are rare, benign tumours of odontogenic origin. They are slow-growing, locally invasive, and commonly affect the posterior maxilla and mandible. These tumours were first described by Cusack in 1827 [1]. They are the most common odontogenic tumours in Africa, and the second most common odontogenic tumours in the United States [2-5]. The global incidence of these has been estimated to be 0.5 cases per million people per year, with their peak incidence occurring between 30-60 years of age [6]. They most often present as a painless swelling of the jaw [7], with up to 35% identified incidentally on radiographs [8]. Pain can be present if there is bleeding following fine needle aspiration [9]. Paraesthesia, tooth resorption, and tooth displacement are uncommon findings with these tumours [10]. These tumours have a predilection for occurring in the posterior regions of the jaws, with the mandible accounting for up to 80% of all cases [11].

Maxillectomy or maxillary resection is defined as surgical removal of a part, or all of the maxilla [13]. The maxilla's central location in the facial skeleton unifies the orbits, zygomatic maxillary complex, nose, and stomatognathic complex into a functional and aesthetic unit [14]. The maxilla provides the structural support connecting the skull base to the occlusal plane, resists the forces of mastication, anchors the maxillary dentition, provides a separation between the oral and nasal cavities, forms the floor of the orbit supporting the globe, and supports the facial musculature. The bony and soft tissues constituting the midface are supported by the maxilla and provide much of the facial contour and profile giving each person a unique appearance [15–17].

Reconstruction of maxillectomy defects remains a considerable challenge because the 3-dimensional architecture of the midface serves both functional and aesthetic roles. Based on these considerations, the final goals for midface reconstruction should ideally be [18]:

(1) to give support to the orbital content, thus minimizing changes in globe position, orbital volume, eyelid functions and treat the exenterated orbit cosmetically;

(2) to maintain a patent nasal airway and oronasal separation creating sufficient platform for mastication, speech quality, and potential dental rehabilitation; and

(3) to restore an adequate and symmetric facial contour with the other side of the face.

Additive manufacturing (AM), or better known as 3D printing (3DP), describes a number of processes where a product is fabricated through a layer-wise construction method. The Direct Metal Laser Sintering (DMLS) AM process at the Centre for Rapid Prototyping and Manufacturing (CRPM) can offer a unique solution for the manufacturing of custom-designed maxillofacial implants, using Ti64 (Ti6Al4V).

Vandenbroucke & Kruth (2007) continue to state that because of technical improvements of layer manufacturing (LM) processes and the possibility to process different metals (and compounds), Rapid Prototyping (RP) has moved beyond its initial applications into rapid manufacturing (RM). They also point out that the progress made could benefit medical and dental applications beyond polymer applications for visual (anatomical) models or single-use surgical guides, to also support the manufacturing of functional implants or prostheses.

This paper presents factual evidence that the process chain based on customized manufacturing has evolved to a level of maturity which can be replicated with confidence.

2 CASE PRESENTATION

2.1 Clinical report

A 54-year old female patient was referred to the surgical team for a resection of a tumour in her left maxilla. Clinical and radiographic findings revealed that the tumour filled the entire left maxillary sinus, and measured 60x50x40mm in size.

2.2 CT conversion

Due to the extent and complexity of the defect, it was decided to fabricate an anatomical model of the hard tissues for planning a possible fabrication of a Ti6Al4V laser-sintered frame for the patient. Computer Tomography (CT) was used as a starting platform and the Digital Imaging and Communications in Medicine (DICOM) files from the scanner were converted to Standard Triangulation Language (STL) format (Figure 1) using Mimics™ dedicated software from Materialise®. The software allows altering the greyscale values from the DICOM images to differentiate between soft tissue and bone.

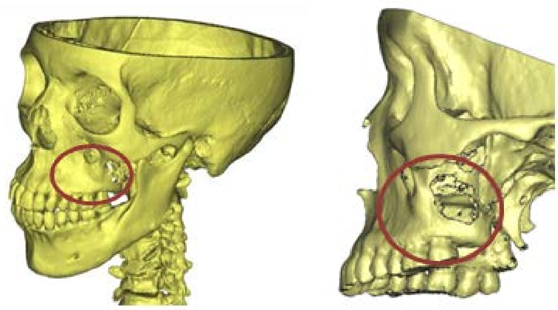

Figure 1 - CT conversion to STL format

2.3 AM of pre-operative model

The region of interest was then masked and calculated as a 3D model, which was exported as a STL file, sliced using RP Tools, and sent to the AM machine to manufacture the planning model. The CRPM did the CT segmentation of the skull and produced the 3D model in an EOS P385 Laser Sintering machine in PA 2200 polyamide material at 150 µm layer thickness (Figure 2).

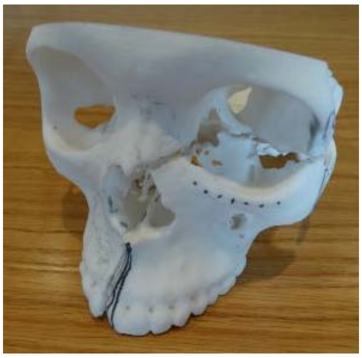

Figure 2 - Skull replica manufactured using Additive Manufacturing in PA 2200 polyamide material

The treatment plan involved a complete resection of the tumour with simultaneous reconstruction using a custom-made titanium framework to replace the resected bone. The nylon model was sent to the surgical team to be cut where the bone resection was planned (Figure 3)

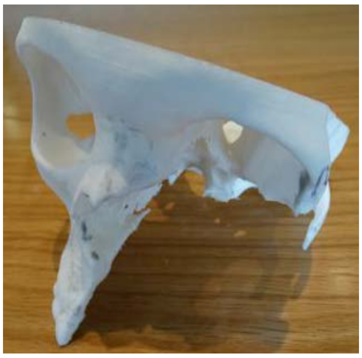

Figure 3 - Nylon model cut where the bone resection was planned

2.4 Reverse engineering and design of titanium implant

The CRPM had only two weeks to design and manufacture the Ti6Al4V implant, due to the severity of the tumour. Furthermore, the prosthodontist made a wax model of the planned titanium frame (Figure 4).

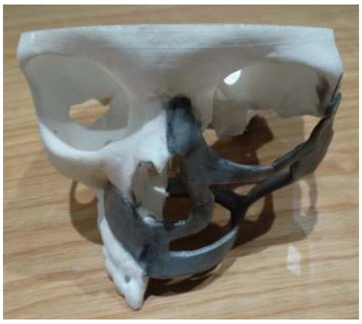

Figure 4 - Wax model of the planned titanium frame

The wax model and skull were reverse-engineered using a Minolta 3D camera and Geomagic® software (Figure 5). The reverse-engineered geometry was used to identify the boundaries and fixation areas of the planned implant.

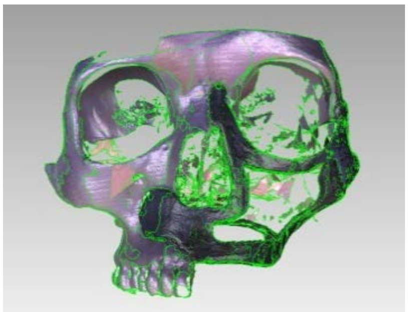

Figure 5 - Reverse engineering data in Geomagic® software

The 3D data were imported into 3-MATIC® (from Materialise) in order to design the implant (Figure 6).

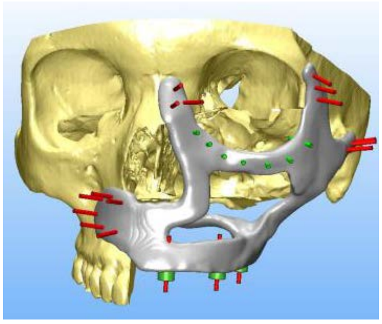

Figure 6 - Implant design done on 3-MATIC®

3 AM OF BIO-COMPATIBLE TITANIUM IMPLANT

3.1 DMLS

The implant design was exported as an STL file, which was converted to a slice file and transferred to an EOS M280 DMLS machine. The implant was manufactured from a biocompatible Ti6Al4V (ELI) powder of sub-40 µm particle size (Figure 7).

Figure 7 - DMLS implant in Ti6Al4V

The DMLS implant was removed from the titanium substrate. The support structures were removed and the implant was manually polished. The implant's fitment was checked on the pre-operative model (Figure 8).

Figure 8 - Checking the implant's fitment on the pre-operative model

A cutting guide (Figure 9) was designed and manufactured in nylon on the EOS P385 machine. The surgeons used this guide to remove the affected bone at the correct angles.

Figure 9 - AM nylon cutting guide

The DMLS titanium prosthesis was successfully implanted during a nine-hour operation (Figure 10). The patient was transferred to the Intensive Care

Unit and a week later to a general ward. The post-operative review was good and many valuable lessons were learned from this case study.

Figure 10 - DMLS Ti6Al4V prosthesis in position

The swelling, as shown in Figure 11, was due to the soft tissue harvested from the patient's forearm and transplanted into the oral cavity. This soft tissue was implanted to create a separation between the oral and nasal cavities.

Figure 11 - Post-operative review one month after the operation

3.1.1 Timeline for design and AM of maxilla

The CRPM only had fourteen days from receiving the patient data to the operation due to the severity of the tumour. The process steps are shown below:

- CT translation, pre-operative model – 2 days
- Surgical planning & wax mock-up – 1 day
- Reverse engineering – 3 hours
- Final design – 3 days
  - Design time – 19 hours (implant and surgical guide)
  - The remainder of the 3 days was for consultation and approval
- Manufacturing – 2 days (including support removal and stress relieving)
  - DMLS – 18 hours
- Polishing – 2 days
- Micro CT scanning – 1 day
- Heat treatment – 1 day
- Cleaning and packaging – 2 days
- Operation – 9 hours

Compared to:

Conventional manufacturing – 5 weeks

or

Additive manufacturing overseas at a cost of $17000 - 4 weeks

3.2 Challenges encountered with DMLS implant manufacturing

Figure 12 shows a summary of a proposed workflow which must be adhered to for certification of the DMLS process

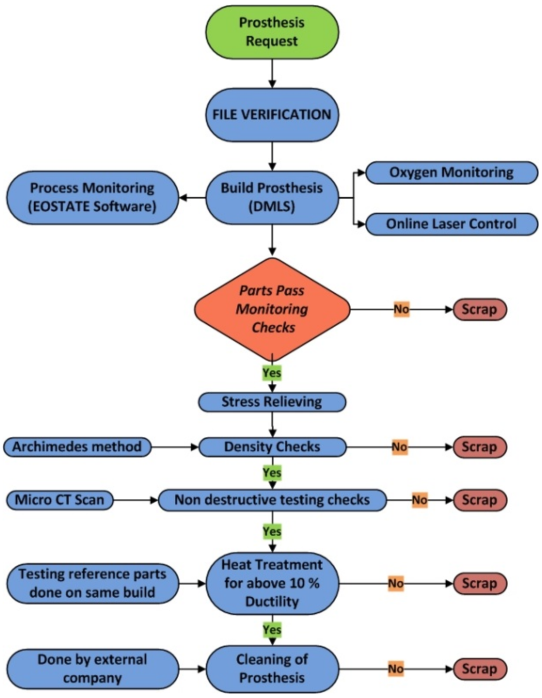

Figure 12 - The proposed AM of titanium implants workflow (author's own creation)

The DMLS process uses a cold bed platform which induces high residual stress in the manufactured part. The parts need to be stress-relieved at 650°C in an argon atmosphere while still fixed on the titanium substrate. Initial research showed that between 76 to 81% of the residual stress can be removed with this stress-relieving cycle [12]. In this study, the researchers used recrystallizing, duplex and beta-annealing processes to further remove the residual stress to levels up to 97%. As-grown the parts are still too brittle for medical use and need to be heat-treated at 1000°C to increase the elongation to above 10%, as required for medical implants. Further in-depth research needs to be conducted to fully quantify residual stresses, as well as optimise stress-relieving and heat-treatment cycles. In the current practice, the part integrity is tested by scanning all the implants using X-ray micro- computer tomography (microCT). For this, a commercial system from the Central Analytical Facilities at Stellenbosch University (SU), a General Electric Phoenix V|Tome|X L240, is used. X-ray settings are 180 kV and 160 µA, using a directional X-ray source. This is done to detect any microscopic voids and cracks that could cause implant failure due to fatigue. The surface fit function allows for a good 3D visualization, as shown in Figure 13.

Figure 13 - Post-operative review one month after the operation

The part showed no voids, but loose powder was seen inside the blind hole (Figure 14).

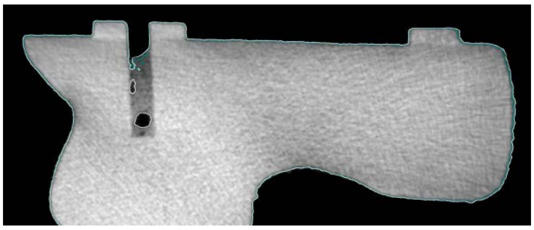

Figure 14 - Powder trapped inside blind hole

Furthermore, test pieces for destructive testing (Figure 15) are manufactured on the same platform as the implants and are tested in an as-grown and heat-treated state. Results are shown in Table 1.

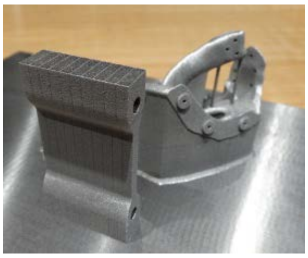

Figure 15 - Test pieces for destructive mechanical testing

Description		UTS (MPa)	Elongation (%)
As grown	Mean of 3 specimens	1155	4.12
After heat treatment	Mean of 3 specimens	850.30	11.88

Table 1 - Tensile test results

4 CONCLUSIONS

It was possible to successfully complete this extremely difficult case study in only two weeks. Considering the timeframes given by the surgeons, it would have been difficult to manufacture the implant using conventional manufacturing techniques. The wax mock-up made of the cutting guide on the pre-operative model by the prosthodontist saved around 10 hours in design time. The part integrity proved to be good as the microCT scan showed no voids or cracks inside the implant. The microCT scan was done at 85µm slices.The heat treatment increased the ductility from 4% (as grown) to above 10%, which is required for implants.

This case study shows that AM can be successfully used in the manufacturing of patient-specific implants. Similarly previous cases by the same team have developed the process chain into a value chain of progressed maturity level. Process parameters are now known and parameter boundaries are set to ensure confidence in quality consistancy. 100% inspection of part integrity by microCT is retained to build out the knowledge database and confidence.

Adequate confidence has now been demonstrated that the value chain can be further optimized and predictive models on cost and time applied. Several unpublished design for manufacturing safeguards are still employed, that may become unnecessary as DMLS technology continuously improves. The presented value chain can therefore be agrued progressively matured by the complexity of the case study.

5 ACKNOWLEDGEMENTS

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7 BIOGRAPHY

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Simulation in Machine Tool Design - From Systems for Experts to Encapsulated Complexity

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Abstract
Simulation is one of the most important methods in production engineering research. The advantages regarding product optimization, cost reduction and shorter time-to-market are well known. However, the transfer of new simulation technologies into practice is often hindered by modelling complexity, information availability and a lack of expert knowledge. The problem can be tackled by a shift in model design. Today, engineers describe "how the simulation model is designed" which requires that the engineer has to think in the scope of cause and effect of the modelling system. This approach implies extensive familiarization with the modeling methodology making practical application difficult. A new approach is to enable engineers to build models in the way "how the real system is designed", e.g. by maintaining the physical topology of the real system in the model. Therefore, we propose to use models that encapsulate mathematical and logical descriptions within component, making it possible to design models out of connected component-models. The approach will be presented with an example from machine tool design.

Keywords
Design of products, systems, families and platforms; Variety management techniques; Mathematical Optimization; Simulation

1 INTRODUCTION

Simulation can be defined as the execution of an experiment based on a (digital) model to understand or predict the behavior of the modeled system [1]. Simulation is applied if real experiments are costly or not possible and if the governing system equations cannot be solved analytically. Latter is mostly the case if the behavior description contains (non-linear) differential equations, recurrence relations or automata. The advantages and disadvantages are quite clear: Simulation can provide a good basis to analyze and optimize system behavior, but the results are mostly useless if a sound model, reliable data or specialized skills are not available [2]. Moreover simulation alone does not yield an optimal solution. Rather, the simulation model can be the basis for an optimization.

While the origins of simulation date back to World War II [3], the first practical applications in engineering are found in the 1960s. Simulation became prominent in the field of production research during the 1980s. For example, the number of publications that contain the word "simulation" in the CIRP Annals more than doubled in this decade, from 74 publication (15 % of total) in the interval from 1980-1984 to 186 publications (30 % of total) in the subsequent five years. Today, approximately 40 % of all publications within the CIRP Annals deal directly or indirectly with simulation. It is therefore not exaggerated to state that simulation is one of the most important methods in production research.

But what about the industrial applications of simulation? The primary aim in this case is not to gain a better system knowledge, but to achieve (short term) advantages in terms of time, quality and costs. In other words: Virtual models must yield real benefits for the customer [4]. A recent survey among German manufacturers of machine tools has shown that apart from FEM under static and dynamic loads, simulation methods are not widely applied [5]. While most companies see a high potential in virtual prototypes, applications are often hindered by the reliability of models and the lack of specifically qualified personnel.

This paper therefore analyses how the required effort, expertise and amount of information for simulation can be reduced, while still being able to test the behavioral requirements. The motivation to facilitate simulation is of course not new. Considering that users had to handle source code (e.g. FORTRAN) some decades ago, the tool-support has already greatly improved. Mechatronic simulation of machine tools and production machines, however, still requires a sound background in control engineering and a detailed systems understanding since differential equations have to be formulated and transformed to input-output relationships. The resulting graphical models that comprise the basic building blocks (e.g. integrator, time lag elements, dead time) have a degree of complexity that is often difficult to handle, even for experts, see Figure 1.

This paper follows the hypothesis that the perceived complexity by the engineer can be reduced if the controlled system is not built-up from basic control blocks (signal-oriented approach) but from components that contain the behavioral equations (object-oriented approach). Thus, the engineer does not need to describe how the system works, but how it is structured. This means, the engineer designs the model of the controlled system with components such as motor, gear and ball screw drive and not with transfer functions. The approach can be seen analogous to the paradigm shift from procedural programming languages to object-oriented programming languages, where complexity can be hidden by encapsulation.

The paper is structured as follows. In Section 2 we discuss the approach of object-oriented modelling and we extend the concepts of [6]. Section 3 comprises an overview of a component library for feed drives that has been presented in detail in a previous paper [7]. In Section 4 illustrates the concepts by an example from machine tool design. In the last section we will give a brief summary and outlook.

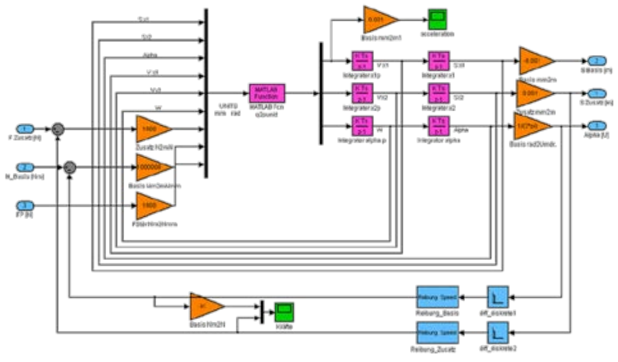

Figure 1 - Exemplary model of a drive system with transfer functions (signal-orientation)

2 OBJECT-ORIENTED BEHAVIOR MODELLING OF MECHATRONIC SYSTEMS

Different methods can be applied to analyze the behavior and functionality of mechatronic systems. One method is to describe the individual elements with transfer elements and to plot the frequency response of the transfer function in the form of a Bode diagram. For simple cases with linear elements, poles and roots as well as optimal controller settings can be calculated analytically, as known from basic control engineering.

With increasing system complexity – e.g. induced by non-linear elements, meshed control loops and multi-mass oscillators – analytical methods come against their limits and computer-aided numerical calculations are necessary to analyze the system behavior. The direct method is to model the system in the form of first-order differential equations in a mathematical programming environment such as MATLAB or MATHEMATICA. Therefore, the engineer has to reformulate the differential equations into a form that can be handled by the solver.

Signal-oriented approaches such as MATLAB/ Simulink release the engineer from any mathematical reformulations by decomposing the system into elementary input-output relationships. For better comprehensibility, signal-oriented approaches typically also enable the composition of hierarchical models, i.e. the design of blocks from sub-blocks. However, models can usually not be modularized in a way that reflects the topology of the real physical system since the components of the real system are reactively coupled [1]. Thus, it is mostly not possible to obtain a 1:1 mapping between real and virtual components with signal-oriented approaches.

Object-oriented approaches, in contrast, make a 1:1 mapping possible. The equations that describe the behavior of a specific component are encapsulated in the component. This improves intuitive comprehensibility, extensibility and reusability and allows the design of model libraries. Object connectors and Differential Algebraic Equations (DAE) are key concepts of object-oriented behavior modelling that are described in the following sections.

2.1 Connectors to Describe System Topology

The design of a component topology requires connectors that describe the interactions between components. An electrical resistance, for example, cannot be connected to a purely mechanical component, while an electric motor has both electrical and mechanical connectors. The connectors lead to additional equations which relate the individual potential and flow parameters (d and f) of the n connections at a node:

$$d_1 = d_2 = \ldots = d_n \,, \tag{1}$$

$$f_1 + f_2 + \ldots + f_n = 0 \,. \tag{2}$$

In an electric network the difference variable is the voltage and the flow variable is the current. Considering (2) it is important to have a consistent definition of positive and negative current for the connectors, e.g. positive current for the inflow of positive charge into a component and vice versa, see Figure 2 a). For mechanical models, force is usually chosen as the flow variable and velocity as the difference variable [1], see Figure 2 b). In analogy to electric networks, a positive force at the outflow port causes the elongation of a spring.

2.2 Behavior Modelling with DAE-Systems

While the connectors comprise a textual description according to (1) and (2), the equations inside the components relate the variables at the connectors with the variables and parameters of the component. Before simulation, Differential Algebraic Equations (DAEs) are generated from the textual model description. DAEs are the basis of object-oriented modelling. They allow to model objects independently from topology in which they are used. For example, the model of a motor does not change whether it is elastically or rigidly coupled to a mechanical system.

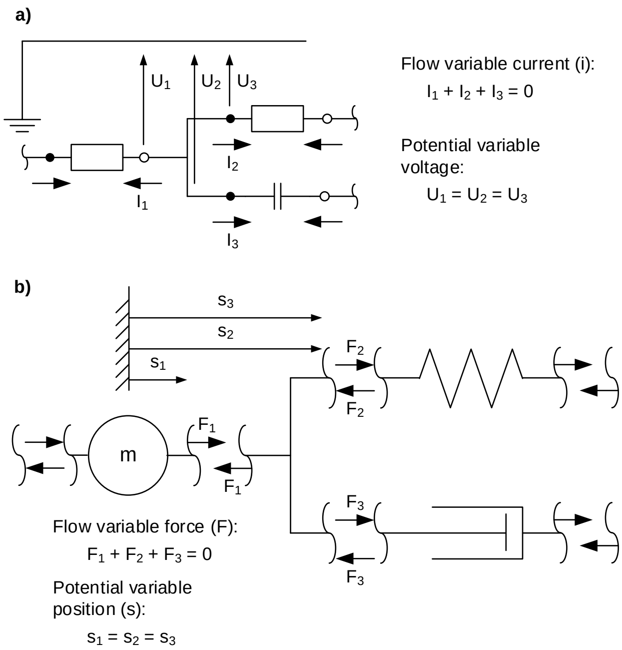

Figure 2 - Flow and difference variables in electrical and mechanical networks based on [8]

DAEs present certain challenges to numerical solvers. The difference between DAEs and differential equations is illustrated in the following example of a rigidly coupled feed drive, see Figure 3.

In the considered case not the torque of the motor M_M, but the velocity of the axis v_{in} is specified in the form of an input signal. We assume that no external force is applied on the axis, i.e. $F_2 = 0$. Analytically, the resulting motor torque can be calculated easily by taking the derivative of the velocity signal v_{in} and substituting it into the equation

$$M_M = \left(\left(J_M \cdot i + \frac{J_{\ddot{U}}}{i} \right) \cdot \frac{2\pi}{h_{Sp}} + \frac{h_{Sp}}{2\pi \cdot i} \cdot m \right) \cdot \dot{v}_{in} \, . \qquad (3)$$

In the object-oriented model each inertia adds two state-variables for position and velocity to system. Therefore, we obtain a system of differential equations:

$$\begin{bmatrix} \dot{\omega}_1 \\ \dot{\varphi}_1 \\ \dot{\omega}_1 \\ \dot{\varphi}_2 \\ \dot{v} \\ \dot{s} \end{bmatrix} = A \begin{bmatrix} \omega_1 \\ \varphi_1 \\ \omega_1 \\ \varphi_2 \\ v \\ s \end{bmatrix} + B \begin{bmatrix} M_M \\ M_1 \\ M_2 \\ M_3 \\ F_1 \\ F_2 \end{bmatrix}, \qquad (4)$$

where the matrix A relates the state variables and their derivatives, and B corresponds to the torque equilibrium. If the couplings between the inertia elements were elastic, the state variables could be chosen independently from each other. Rigid coupling, however, leads to constraint equations that relate state and algebraic variables, i.e.

$$0 = C \begin{bmatrix} \omega_1 \\ \varphi_1 \\ \omega_2 \\ \varphi_2 \\ v \\ s \end{bmatrix} + D \begin{bmatrix} M_M \\ M_1 \\ M_2 \\ M_3 \\ F_1 \\ F_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v_{in} \\ 0 \end{bmatrix}. \qquad (5)$$

Here, the matrices C and D relate position values and torques/force according to the transmission ratio of the gear and slide.

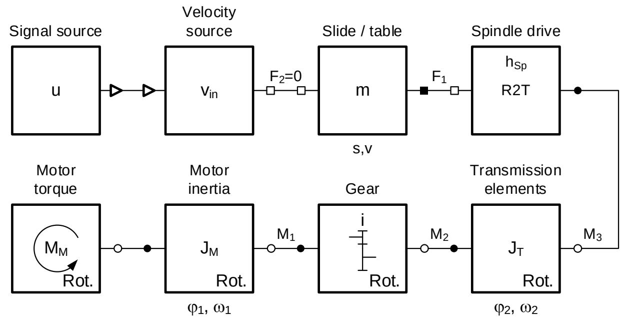

Figure 3 - Rigidly coupled feed drive with gear and lead screw

To obtain a model that can be simulated, the constraints in (5) are used to reduce the number of differential equations in (4). In other words, a DAE-solver manipulates the equations to obtain a system of ordinary differential equations of lowest possible dimensionality. Therefore, only one state variable is specified at t = 0 and all other state variables follow from (4) and (5).

The example illustrates that the object-oriented approach does not require any manual reformulations of the problem, but instead the computational effort for the simulation increases. Lower modelling efforts are traded off against higher computational costs. The DAE system is automatically transformed into a solvable form by manipulating differential and algebraic equations (so-called index reduction). Therefore, it is more challenging to simulate object-oriented models than signal-oriented ones that describe the system directly with the lowest possible dimensionality [1]. However, DAE systems of physical systems can generally be solved efficiently with special algorithms, e.g. [9,10]. Further, the object-oriented approach has the advantage that several different input signals can be used with the same model topology. The torque of the motor can be calculated from the trajectory of the slide and vice versa. Therefore, one and the same model enables to calculate the physical effects from the cause (forward simulation), but also to compute the necessary physical causes from the required effects (backward simulation) [11]. This facilitates requirement testing without parameterization of controllers.

2.3 Languages and Software for Object-Oriented Behavior Modelling

There are several modeling languages and software environments available for object-oriented modeling and simulation, e.g. VHDL-AMS for the simulation of integrated circuits, gPROMS for process systems engineering and Modelica as well as MATLAB/Simscape with a focus on mechatronic systems.

MATLAB/Simscape and Modelica are semantically quite similar. MATLAB/Simscape has the advantage over Modelica that the well-tested MATLAB-Toolboxes for control engineering are directly applicable to the object-oriented models. For this purpose, converter blocks generate MATLAB/Simulink signals from physical variables and vice versa. However, MATLAB/Simscape is a proprietary language and the models can only be designed and compiled within the MATLAB-environment. In contrast, Modelica is an open and non-proprietary standard that is managed by a consortium of organizations and individuals. It has been established in the year 1997 [12], ten years before MATLAB/Simscape was published. Modelica models can be developed and simulated with different software products, e.g. Dymola (Dassault Systèmes), LMS Imagine.Lab (Siemens) or SystemModeler (Wolfram). Further, two open source environments are available: OpenModelica and JModelica.

The Modelica Standard Library contains components of different physical domains such as electrics, mechanics, heat transfer and fluidics as well as the necessary elements for continuous and discrete event control systems. Additionally, several free and commercial model libraries are available, e.g. for hybrid drives, belt drives, heat exchangers and linear system analysis. The large number of libraries and software tools are reasons for an increasing application of Modelica in science and industry. Also the models of this work are based on Modelica in order to use these independently from the software tool.

3 MODELICA LIBRARY FOR FEED DRIVES

Object-orientation enables the design of model libraries. Engineers can then create new models by selecting, parameterizing and connecting components from the library. Models can also be composed by components from different libraries as long as the connectors are compatible.

Model libraries are especially useful for designing feed drives of machine tools and production machines for two reasons. First, feed drives are based on a limited number of component types such as permanently excited synchronous motor, ball screw drive and timing belt drive. Therefore, the size of the library is easily manageable. Second, feed drive designers often lack the experience to create their own component models. Using components from the library, however, is intuitively understandable since the symbols of the objects are taken from the domain of application.

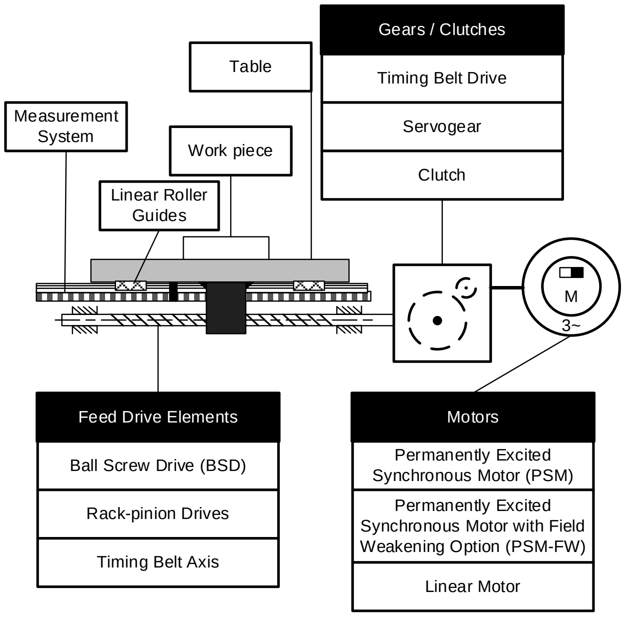

Figure 4 - Main components of the Modelica library for feed drives

The Modelica library for feed drives contains the typical components of a feed drive system, see Figure 4. The components can be parametrized with data that is available from supplier catalogues. On the one hand, this data comprises physical parameters such as torque constant, resistance and inertia. On the other hand, the components are parameterized with limiting data, e.g. maximum torque or rotational speed. While the first type of parameters is required for the physical behavior, the second type is necessary for requirement testing. The models are validated by measurements provided by suppliers and by own measurements. The following section illustrates the application of the library. For a detailed description of the library the reader may refer to [7].

4 APPLICATION EXAMPLE

In this example, a permanently excited synchronous motor of type Siemens 1FT7086-AC7 drives a table with mass $m_L = 2500\ \text{kg}$ by means of a toothed belt drive (TBD) and a ball screw drive, see Figure 5. All components are parameterized with data available from supplier catalogues. Maximum acceleration ($a_{L,max} = 10\ \text{m/s}^2$) and velocity ($v_{L,max} = 18\ \text{m/min}$) are specified through an input signal (ramp). The aim of the example is to minimize the armature current by varying the transmission ratio i and the spindle pitch h_{Sp}. In addition, the limit constraints of the components have to be satisfied.

Multiple simulation runs with different values for the gear transmission ratio i and the spindle pitch h_{Sp} yield Figure 6. On the one hand, Figure 6 illustrates how the armature current I_A depends on h_{Sp} and i. On the other hand, the permissible domain is depicted, in which none of the constraints are violated. Therefore, the engineer can determine optimal values for h_{Sp} and i from the simulation results.

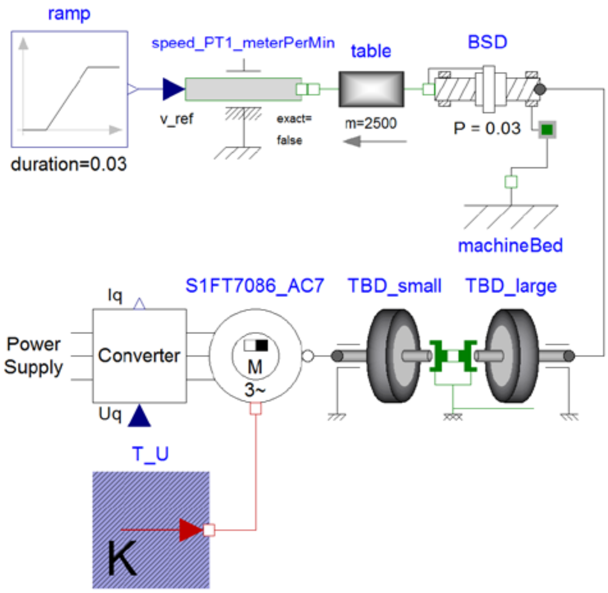

Figure 5 - Feed drive with toothed belt drive and ball screw drive

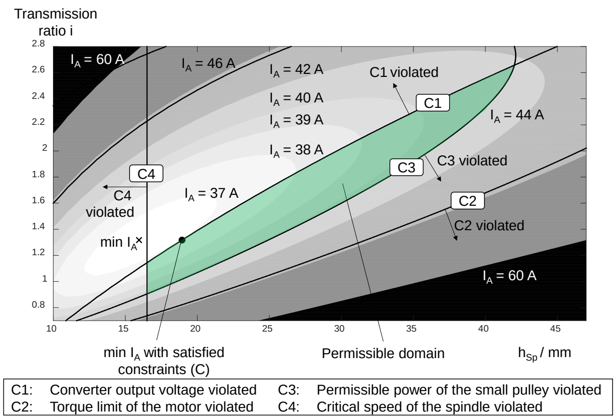

Figure 6 - Feed drive with toothed belt drive and ball screw drive

The armature current I_A is dependent on the maximum acceleration, the transmission ratios, the mass of the table and on the inertia of the motor J_M, the small pulley J_{R1}, the large pulley $J_{R2} = i^4 \cdot J_{R1}$:

$$I_A = \frac{a_{L,max} \cdot i}{h_{Sp}/2\pi}\left[\frac{1}{i^2}\left(m_L\left(\frac{h_{Sp}}{2\pi}\right)^2 + J_{Sp} + J_{R2}\right) + J_{R1} + J_M\right] \quad (6)$$

The resulting contours of (6) have an ellipse-like shape that is also reflected in the simulation results, see Figure 6. Starting from a relatively small transmission ratio i, the armature current decreases with increasing i since the effective moment of inertia of the load is reduced. At a certain point, however, the required current increases again as the moment of inertia of the large pulley depends on the fourth power of its diameter. The minimum armature current of $I_A = 36{,}5\text{ A}$ corresponds to at $h_{Sp} = 16\text{ mm}$ and $i = 1{,}3$ (see $\min I_A$ in Figure 6).

But for this optimal point, the voltage limit is violated, i.e.

$$U_{U,max} \le \sqrt{3} \cdot \omega_{M,max} \cdot \sqrt{(p \cdot L_D \cdot I_A)^2 + (K_T/3)^2} \quad (7)$$

where $U_{U,max}$ is the voltage limit, $\omega_{M,max}$ the angular velocity of the motor, p the number of pole pairs, K_T the torque constant and L_D the rotating field inductance.

The limit values and the inequality constraints such as (7) are parts of the library components. Thus, the engineer does not need to analyze the simulation results in detail, but accesses violated constraints directly.

So far, the considered degrees of freedom were continuous. But often the engineer is interested in selecting a component form a catalogue. Typically, a component such as a motor has multiple physical and limiting parameters. Each set of parameters then leads to different objective and constraint values. Figure 7 illustrates the results for different pulleys and motors. Pulleys are available only with certain diameters and numbers of teeth leading to discrete values at the ordinate of Figure 7. The motors differ in their size and winding types resulting in different physical and limiting parameters. The armature current and the satisfaction of the voltage constraint are dependent on both, the selected motor and pulley. The minimum armature current is reached with the motor 102-AB7 and a transmission ratio close to one.

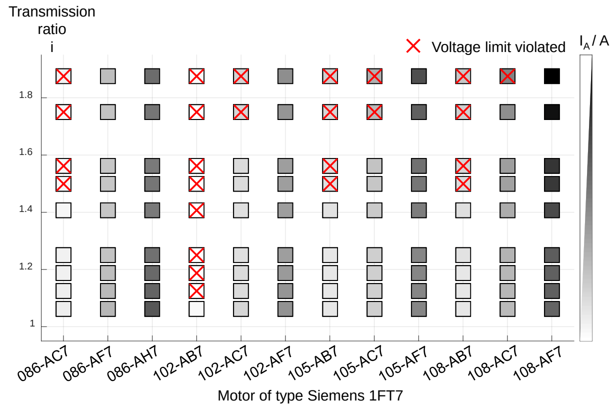

Figure 7 - Feed drive with toothed belt drive and ball screw drive

5 CONCLUSIONS

This paper discussed the concept of object-oriented behavior modelling as a means to leverage the potentials of simulation in an environment with tight time constraints that lacks simulation expertise and proven models. Object-orientations enables engineers to develop models with a topology that directly resembles the topology of the real system. In comparison to the conventional signal-oriented models, this approach improves the intuitive model comprehensibility as well as the maintainability and reusability.

Object-oriented behavior modelling is a growing research and application field. More applications within production engineering will increase the availability of accurate models that can easily be used by experts and non-experts. In this context, our Modelica feed drive will soon be made available to the public. One aim of this paper is to motivate the production engineering community to develop and share model libraries.

Object-oriented behavior modelling can be extended by methods for optimization, frequency analysis and system identification. These features will further facilitate the process of designing machines whose requirements are well tested before the first prototype is built.

6 ACKNOWLEDGEMENT

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8 BIOGRAPHY

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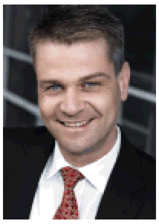

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Incertitudes in Design Decisions – Impediments or Instruments?

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Abstract

In product development, reasoning based on information content progressively complements sheer process driven approaches. Here, the coherent set of design decisions is seen as the backbone that enables the design team to initiate, substantiate and assess the evolvement of development trajectories against the context and the requirement specification. Habitually, design decisions are seen as means to reduce uncertainty in development cycles, while implicitly disavowing or ignoring the elusivenesses of the decisions themselves. A different approach is taken here, by making the role of uncertainty, ambiguity, volatility and indeterminism in decision making explicit, both as concerns the underlying information and the process itself. For now, this does not yet overthrow the way in which products are developed, but it does substantiate an understanding of decision accuracy, reliability and sensitivity. With this, product developers are challenged to explicitly address decisions by purposefully employing knowledge on the incertitudes inherent to product development.

Keywords

Design method, decision making, uncertainty

1 INTRODUCTION

Decision making has both expected and unexpected impacts. Even a straightforward, simple choice may lead to unforeseen consequences, with a snowball effect as extreme. Next to such aftereffects, the elusiveness of decision making in itself will also affect its predictability. Oftentimes, designers are not aware of this elusiveness, or lack substantiated means of incorporating it in decision making. Therefore, their only option is to ignore it all together by entirely focusing on the information that is explicitly available. As a result, this information might be mistakenly perceived as correct, certain and unfaltering. This situation does not adhere to lifelike decision making processes, moreover, it results in situations where decision processes convert potentially unreliable information in outcomes that are presented as sound. Obviously, this brings a false sense of exactitude to evolving product definitions and development cycles.

In doing justice to the role and importance of elusiveness in decision making, incertitudes have to be seen as instruments rather than as impediments. To establishing this, the information that underlies decision making should be the pivot of development cycles. However, as design cycles are often seen as being process oriented [1], the information content is often hardly more than a cluttered, complex and potentially oversized collection of useful, but also contradictory, shattered and partially irrelevant information. Especially in the early phases of the development cycle there is a considerable risk that the connection between the design process and the information content is lost, causing disproportional problems in downstream processes. However, the risk of losing this connection is certainly not reserved for the start of development cycles.

2 IS ONLY THE FRONT-END FUZZY?

Product developers excel in generating clear-cut product definitions from ideas, concepts, promises and gut feeling. It is the creativity and workmanship of the designers that allows them to cope with the vagueness and indefiniteness that characterise those development cycles – especially in the earlier stages. From a managerial perspective, however, it is far more difficult to value the elusiveness of development cycles. In an attempt to make the design process seizable, it is often subdivided in three sections [2]:

- fuzzy front end (FFE)
- new product development (NPD) process
- commercialization

In this context, the fuzzy front end is often referred to as the set of activities that come before the formal and well-structured NPD process [3]. With this, the 'chaotic, unpredictable, and unstructured' activities are separated from the NPD processes, which are assumed to be 'typically structured', with an assumed formalism relating to a prescribed set of activities and questions to be answered [2,4].

Interestingly enough, this managerial divide between the fuzzy front end and the 'actual' new product development clashes with the typical designer's perspective. After all, designers purposefully try to integrate downstream aspects (costs, feasibility, manufacturability, packaging …) in early ponderings and decision making – expressly disclaiming this divide. Moreover, from a design perspective, the projected tangibility and predictability of the new product development process is not necessarily a reality – to say the very least.

In other words, where the managerial (meta-) perspective might indeed be capable of separating the ‘unassignable processes’ in the fuzzy front end from the ‘assignable processes’ in the new product development, the design perspective has its focus on the purport of the processes – being comparably uncertain in both cases.

If this design perspective is taken to extremes, the imposed phasing in development cycles cannot be leading. Rather, the development cycle emerges as a set of processes that conjointly and dependently contribute to the advancing knowledge and control of the product under consideration. The processes might adhere to a presupposed phasing but might as well follow a completely different route. Moreover, the processes are no fixed procedures, nor is their sequential execution self-evident. It is not the activity or phasing that defines the metre of development cycles, but the aim of the activity; the expected added value for the new product under development.

Starting from a situation with (usually) a shortage of complete, decisive and reliable information, the development cycle (with all its explorations, iterations endeavours and reconsiderations) constructs a definition of the product that aims to be clear, unambiguous and complete. Simultaneously, the requirements specification is observed, while also adapting and repleting it [1] in the context of e.g. the company’s product strategy, improved understanding of the problems at hand or added consumer insights.

In such an endeavour, certainly some anchor points can be helpful to constrain the process, but these have a mostly managerial meaning. The recognition of the fuzzy front end as a phase is merely one of such anchor points. Although potentially these phases are powerful mechanisms to control projects, they should not be confused for a blueprint for actually executing a development cycle.

At the same time, from an overall perspective, the start of a development cycle indeed seems more precarious than the later stages. However, this may be caused by the fact that many stakeholders (implicitly) tend to assess the amount of uncertainty as a ratio against the amount of information already established. Obviously, if hardly any information is available, small indistinctnesses can drive this ratio to extremes. In the later stages of product development, when the product definition is much more elaborate, the relative impact of indistinctness on this ratio may appear much smaller. However, while building the product definition, every next step has a certain (absolute) amount of uncertainty involved. Interestingly enough, this amount is well-nigh independent on the magnitude of the set of all the future decisions looming. This is caused by the reflection that the vast majority of these decisions cannot yet carry meaning for or cannot yet influence the next design step. So, although the future impact of decisions in the earlier stages of product development may be more far-reaching, the actual amount of indistinctness that designers have to deal with does hardly change over the development cycle. In other words, for designers, every next step has fuzzy aspects of its own.

With this, a development cycle is a venture that has a rolling horizon, in which every step attempts to produce an evolvement of the product definition, by assimilating the information, context and indistinctnesses that characterise the current state of affairs. Therefore, the fuzzy front end is not just the starting point of a development cycle. It rather is the ever-fuzzy next step that builds on the already consolidated product definition.

3 DECISION MAKING AS VALUE ADDING ACTIVITY

In the ever-fuzzy evolvement of the product definition, designers continuously aim to translate abstract requirements into well-defined solutions. Designers are particularly skilled in dealing with the uncertainty, ambiguousness and unpredictability that characterizes the development cycle. It is the problem solving focus, creativity and the ability to make decisions under uncertainty that allows a designer to create new ideas and materialise the pursued added value [5]. In this, decision making is the activity that determines the preferred course of action. Simultaneously, there is an important aspect of consolidation in decision making; determining which available option is currently best and which alternatives are abandoned. Consequently, decision making can be understood as a design activity that fosters and consolidates both the product definition and the design rationale.

As such, there is a clear relation between decision making and the information content in a development cycle. Even more, if designing is understood in terms of creating (new) information content [6], rather than a predefined course of actions, then decision making is the elementary activity in establishing that information content. Consequently, the coherent set of design decisions is seen as the backbone or scaffolding that enables a design team to initiate, substantiate and assess the evolvement of development trajectories against the context and requirement specification. Decision making should therefore be understood as a value adding activity.

As there is no conclusive, universal approach for decision making, this paper uses a generic model

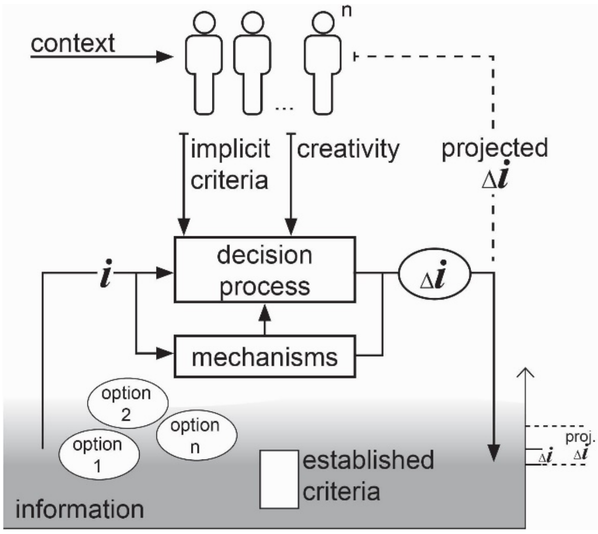

Figure 1 - Decision making explained in terms of information transformation

(figure 1) that addresses decision making as an activity that converts a given input in a certain output, by using mechanisms while adhering to control that is exerted. Although this model assumes that the decision is an activity, it actually emphasises decision making as a transformation of the information content. This implies that decision making leads to an enrichment or fortification of the information content – even if the design team decides to mercilessly kill a concept.

Obviously, not everything in a development cycle is available as concrete, tangible and readable information. Tacit knowledge and implicit decision criteria reside in the assessors of that information: actors. As the main resource of the decision process, actors not only bring (in)tangible control factors into a decision process, actors also introduce creativity. This implies that actors in a decision process act as a kind of referee while simultaneously participating in the game. The complexity of this role is emphasised by the fact that actors are subjective to contextual factors influencing decision processes. Moreover, actors usually have an expectation about the outcome, indicated by the projected delta-information (Δi). In other words, efforts required to establish the information content are not necessarily predictable, straightforward, or unequivocal.

To better understand decision making processes, a distinction is made between explicit and communicable information (like models, facts, data, images, text, correspondence or software) versus implicit information that knowingly or unknowingly is embayed by the actor(s) involved. Both information sources provide the prerequisites (goals, alternatives and projected consequences) for a decision to be made, although there is a clear distinction. The explicit information, various options and previously established decision criteria, represent the deterministic fraction of the design process. Accordingly, tacit aspects such as implicit decision criteria, contexts and creativity denote the indeterministic nature of decisions. By combining both fractions, the inevitable discrepancies between the prospected outcome (i.e. the projected Δi) and the actually established change in information (i.e. the actualised Δi) is made visible. In information-based decision support, such discrepancies often emanate from the indefiniteness of development cycles. With this, it is essential to take into account the uncertainties, ambiguousness and volatility inherent to any decision making process – exactly to improve that process.

4 ELUSIVENESS OF DECISION MAKING

This section describes the elusiveness of decision making in terms of volatility, uncertainty, complexity and ambiguity. The acronym 'VUCA', describes the dynamics and indefiniteness of realistic situations while serving as a framework for strategic decision making [7]. Both the inherent appreciation of lifelike decision processes and the focus on the indefinite aspects thereof makes VUCA an appropriate backbone for describing the elusiveness of decision making in product design.

Given the role of information content in decision making, it is essential that VUCA-aspects are not only related to decision making processes, but also to the underlying information. With this, the decision model itself can be more adequately aligned with incertitudes of the information content, doing more justice to the practical conditions in decision making.

4.1 Volatility

Volatility addresses the nature of change. A volatile situation is subject to change, in which timing and the magnitude of events are not necessarily related to the significance of the impact. Oftentimes, a situation is labelled volatile in hindsight, making it a qualitative measure for the instability of a process or situation.

In the decision model of figure 1, the basis of the volatility of a process is represented by the context in the upper left corner. It characterises the change of contextual factors that influence the actors involved. The causes for a volatile situation in a design cycle generally stem from instability. An example is the unanticipated launch of a competitor's product, thus altering the stated purpose of the current project. Volatility can also be seen as a characterisation of inexplicable actor behaviour. Here, the cause of that behaviour stems from a context different than the development environment of the current project.

By means of e.g. risk assessments, volatility of processes can be characterised. However, the step to controlling volatility of processes is well-nigh impossible. For the information content, however, volatility can more adequately be addressed. Here, volatility has everything to do with validity. Even highly volatile information, such as prices for raw material, can be encapsulated by explicitly addressing the validity of information.

4.2 Uncertainty

Habitually, design decisions are regarded as a means to limit or reduce uncertainty. Uncertainty is typically regarded as one of the main causes of hesitation and instability in design cycles. While these adverse effects are undeniable, uncertainty also has a more efficacious influence, as it creates design freedom and enables designers to explore new ideas and create new value. In other words, the absence of uncertainty in a design cycle would disclaim the need for the creation of new products.

When expressed or put into estimates, uncertainty conveys the assessment of the unknown but necessary parts of a development cycle. However, uncertainty is not an allocable, delimited area in a decision process. It is so intertwined with the essence of design that it is in fact ubiquitous. Indefinite product definitions, hesitation about previously established criteria or the unsettled future course of actions: uncertainty is literally present in every aspect of decision making. When expressed in terms of the decision model: literally every arrow and delineation is vague rather than fixed. While this may seem to be an unworkable assumption, it does justice to the reality of decision making in design.

In an attempt to purposefully take into account uncertainty in decision making, a practical divide is proposed between ingrained, uncontrollable uncertainty and uncertainty that is considered to be manageable. The latter is regarded as the probability that a designer can, with some effort, be a little more certain about something.

Although commonly regarded as an inherent part of design, uncertainty is not explicitly reflected in the information that is used during decision making. The available information, especially in digital form, seems to claim a certainty that is not congruent with the uncertain nature of design. Additionally, many decisions are not solely based on explicit information, but are supported by heuristics or gut-feeling [8]. Subsequently, the outcome of decisions is often documented as univocal and objectively valid, if documented at all. This renders a sense of certainty that is not justifiable.

Explicit, exchangeable information and implicit, tacit knowledge used in decision making are mutually dependent, the information employed should therefore also bear the signs of the uncertainty that was or is at play. Information in design should therefore not only represent one, explicit message or value but simultaneously convey the value-range of the information. As such it can not only convey the content but needs to simultaneously address the sensitivity of that information.

4.3 Complexity

Complexity addresses the intricate, entangled systems and situations inherent to design. A complex situation or system consists of many interrelated parts, where the relations between those parts can be unclear or unknown. Moreover, such relations can also bear relevance for other products or projects. To mention just one example of complexity, what starts as a singular stakeholder can appear to be a cohesive network of multiple actors. This punctualisation effect [9] postulates that each entity might be a network of different entities when the context or the environment changes. Consequently, it is impossible (and meaningless) to aim for a univocal consideration of the complexity of a system or a situation.

Moreover, in adding value, designers constantly create new artefacts; in other words, they are used to addressing the undefined while attempting to simultaneously addressing relations between undefined aspects. Complexity is considered to be a rudimentary yet fairly uncontrollable aspect of design. With this, addressing volatility, uncertainty and ambiguity seems an appropriate way to limit the effects of complexity on the consistency of a product definition.

4.4 Ambiguity

Whereas uncertainty is depicted by a range of known and (yet) unknown possibilities, ambiguity characterises situations in which the uncertainties are not knowable [10]. Distinctive ambiguities are predominantly found in the earlier phases of product development, when possible routes are considered and the denotation and impact of processes and entities are unknown or are questioned in the evolving development context.

Ambiguity is a downright consequence of the inevitable differences in interpretation when multiple stakeholders are involved. Even the most obvious, strictly defined entity could still be assigned different meanings by different actors in relating it to, or deducing it in, the actors' real-world context or knowledge. This renders ambiguity a characteristic of the relation between an entity and an individual actor. Each actor has a unique frame of reference that is not only determined by the current status and development cycle, but is also influenced by expertise, interests, previous experience, education and factors such as mood. Joint procedural agreements, ranging from making minutes of a meeting to adopting industry standards can reduce this equivocality, but it cannot banish it. It goes without saying that the burden of ambiguity increases exponentially with the number of stakeholders involved, especially if the stakeholders are only loosely connected to the project.

In design, ambiguity is influenced by the state and condition of the resources used. Information related to such resources (ranging from documents to equipment) is often incomplete and indefinite. Moreover, stakeholders only might have access to partially overlapping information or even separate, detached information on the same resource. Even a difference as simple as having two versions of the same document could cause misalignment and obfuscates mutual understanding. Given the contexts of the actors, even explicit and exchangeable information in a design project does not necessarily allow for univocal interpretation. Although scrupulous and controlled processing might case the manifestations of ambiguity, that is not the encompassing answer to deal with ambiguity. Moreover, the design process might be frustrated, particularly because it is the discrepancy in itself that can be instrumental in fostering new ideas, better comprehension of the design problem and better decision making. Rather than preventing ambiguity, this research aims at purposefully embracing the various denotations of information. This is not done by pointing out the emerging indefiniteness of information, but by explicitly taking into account the different perspectives on the information content.

5 DETERMINISTIC DECISIONS IN A NON-DETERMINISTIC ENVIRONMENT

The way in which information is currently used in development trajectories usually does not do justice to the non-deterministic nature of design. In order for information to be instrumental in decision making, the use and representation of that information should be tailored to its context and purpose. The characteristic indistinctnesses of design should therefore be manifest in the underlying information. Similar to tangible objects under construction, where the status is evidently visible, the information content (i.e. the product definition) should be seen as a workpiece. With this information as the pivot, volatility, ambiguity and uncertainty can become interrelated, meaningful and manageable aspects in the development context. Therefore, information can play a much more direct and active role in decision making. This section describes a generic approach towards incorporating the vuca aspects in information. Also, the potentialities of this approach are described.

Even in non-deterministic decisions, many of the evolvements of the information content are more or less self-explanatory in nature. This yields true for many steps that can be depicted as being routinely and predictable. For designers, assistance in addressing routine matters is beneficial, especially if that assistance can also address incertitudes. For this reason, this research introduces so-called mechanisms (see figure 1). By employing a what-if approach [11], mechanisms can assist designers, by taking on the more routine tasks involved in designing. Mechanisms can be considered as deterministic and autonomous means to reach decisions or make circumstances for decisions explicit, provided that the required input is available. In its broadest sense, mechanisms transform input into output according a predefined and well-established set of operations. These range from algorithms for e.g. strength analysis or workflow assessment, to process descriptions for risk assessment. The output of a mechanism can serve as input for other mechanisms. Therefore, a constellation of mechanisms can be seen as a mechanism in itself, generating more complex output like the assembly costs of a product.

Mechanisms process their input while taking into account three properties of that input: probability, validity and sensitivity. The probability can be used to address the uncertainty and reliability of the subset of information available. The validity of information expresses the terms and conditions that may apply, e.g. an exchange rate for raw material prizes, provisional information, or contextual boundaries that demarcate the legitimacy of the input. The mechanism itself also has a probability property, relating to the level of repeatability, accuracy and reliability of the mechanism itself. For each mechanism, the interdependency between variables determines the sensitivity of each input. Uncertain input factors that highly influence the output, will have a higher impact on the accuracy of the outcome than uncertain input factors with a minor influence on the output. By making such interdependencies explicit, decision makers can much better determine the effectiveness of efforts to reduce the uncertainty of specific inputs.

In decision making, mechanisms are made instrumental in providing insight in the possible consequences. It enables using information as a workpiece and aids in making the (im-)possibilities, contradictions and gaps in the evolving product definition explicit. Evincing the incertitudes that underlie that information not only results in a more realistic representation, but simultaneously reveals the scope and margins of that information. Collating new, emerging information stemming from the decision under consideration with e.g. the requirement specification that reflects the achieved consensus, produces insight and fosters design acumen. This enables continuous awareness on the alignment between the intended purpose and the evolving product definition.

6 CHALLENGE

In the context of this research, the aim is to convert the model of figure 1 into a practicable framework that supports designers and design teams in making decisions in a more deliberate manner. In this, the intangibilities of both the input and the decision making process as well as the exactitude of the output should be taken into account. In earlier research, a powerful underlying information structure for such a framework has already been addressed by means of the so-called actor network [12]. The actor network employs a non-hierarchical way of information structuring that ensures maximum flexibility while simultaneously allowing meaningful information representation. With this, the actor network stresses the relevance of the information content, and allows for effective anchoring of decisions in that content.

Currently, the mathematical underpinnings of uncertainty and sensitivity in (deterministic) decisions and information content are being integrated in the actor network. With this, the foreseen preconditions can be met, and attention can shift to the way in which individual designers and design teams can purposefully address decision making while explicitly making the leverages of incertitudes instrumental. Here, the main challenge lies in establishing an interface with the designers and design team that enables them to focus on the design intent while spending efforts that are in line with the incertitudes of the process. Simultaneously, using those efforts to capture the design rationale is an essential side effect.

7 CONCLUDING REMARKS

Process-driven development methodologies function on a meta-level that is not always logically connected to the daily practise of product designers and engineers. When rigidly applied, process descriptions become oblique ways of working to arrive at design activities that add value to the product definition. This meta-level functioning can hamper designers in doing what they do best: solving problems by creating new products/solutions. Accountability based on progress regarding the process then becomes an unnecessary and inefficient way of control. Instead, the product definition itself should instigate the necessary design activities. Similar to a workpiece, information in development trajectories should serve the designer in considering the next best course of actions.

In this, design rationale should become the reason to record information instead of an imposed consequence and documentation afterwards. Consequently, the transformation of information instigates design activities. In acknowledging the elusiveness of decision making, this research aims to deliberately take into account the incertitudes; making it instruments instead of impediments. By explicitly addressing volatility, uncertainty and ambiguity, information is given a more true to nature representation: a non-definitive status from which the incertitudes can easily be read. For now, this does not yet overthrow the way in which products are developed, but it does substantiate an understanding of decision accuracy, reliability and sensitivity. For the short term, it may change the way in which designers are supported in reaching decisions. In the long run, however, using the information base as the pivot of development cycles can open up new ways of using PLM, CAD and other tools in design cycles.

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Prediction of Geometric Errors of Stamped Sheet Metal Parts Using Deviation Field Decomposition

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Abstract
Stamping process is widely used to fabricate sheet-metal components. Due to the intrinsic nature of sheet-metal parts, it is usually difficult to control the quality of the final shape, surface defects or geometric errors. Additionally, to meet tight GD&T specifications, a proactive prediction technique is required to estimate global/local geometric defects caused by manufacturing steps. Current best practice relies on manual trial-and-error approaches which are far to be optimal and are costly and time consuming. This paper proposes a *model-driven* methodology to forecast geometric errors for given set of process parameters (*forward process*), and consequently optimise (*feedback process*) the process parameters to achieve given quality standards. The methodology is based on: (i) experimental investigation with varying process parameters and subsequently, deviation field extraction by mapping high density Cloud-of-Points with nominal CAD model; (ii) deviation field decomposition; (iii) surrogate model development by mapping decomposed deviation field to process parameters. An industrial case study is used to validate the methodology.

Keywords
Sheet Metal Stamping, Geometric Errors, Deviation Field Decomposition, Surrogate Modelling

1 INTRODUCTION

Sheet metal forming process, such as stamping, is prone to various defects unless the process parameters, forming tools and material variations are optimised and kept under control. Defects can be classified into local (i.e. cracks, wrinkles, cosmetic defects) and global (i.e. dimensional and geometric errors) defects. This paper focuses on geometric errors since they are imputed to impact assemblability and subsequently poor quality of final products [1] [2]. Geometric errors are the result of material or manufacturing process variations such as spring-back errors, fabrication parameter variations [3].

The industrial practice for setting up the process parameters is mainly based on the manual trial-and-error adjustments [4] [5], which involve repetitive experimental tests and multiple parameter tuning. As a consequence, it leads to higher ramp-up time and production cost.

Recently, Finite Element Method (FEM) techniques have been utilised to predict sheet metal defects and to reach optimal and robust design solutions. Many simulation tools are also available to simulate the sheet metal stamping process, such as AutoForm, HyperForm, DYNAFORM, PAM-STAMP, FASTFORM. However, those tools alone does not provide the complete solution to achieve automatic process control and adjustment as demanded by modern manufacturing process (as demonstrated by recent trends in Industry and Academia: Smart Factory, Industry 4.0, Connected Factory, The Factory of the Future [6] [7]). This implies the need to systematically integrate monitoring strategies (both in-line and off-line sensor data) and *model-driven* process control strategy to achieve near-to-zero defect during manufacturing processes.

Figure 1 shows the general framework for closed-loop process control by combining data (such as dimensional and/or geometric product information collected using surface-based scanners) and *model-driven* process control approach.

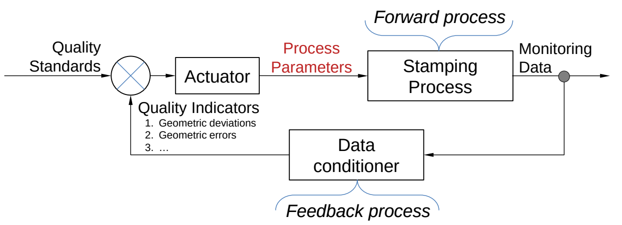


Figure 1 - General framework for closed-loop process control of sheet metal parts.

Model-driven closed-loop process control is understood as capability to keep the process in control by inferring corrective actions through sensing the process (i.e., data collection) and enhancing those data (*data conditioning*) by prediction models. Classical process control strategies are only based on sensing techniques. Although data collection is a necessary step for process control, it is not sufficient for closed-loop control, because of the complex nature of the stamping process along with the inherent variation of *product* (i.e., material thickness) and *process* (i.e., speed, blank holding force) parameters.

This paper provides contribution towards closed-loop process control by identifying the relationship between the geometric errors and product/process parameters. Thereafter, the established relationship can be utilised to isolate the faults and take corrective actions. This will allows to forecast geometrical variations for given set of process parameters (*forward process*), and consequently optimise (*feedback process*) the process parameters to achieve given quality standards.

Current literature is mainly limited to process characterisation with no clear approach to achieve forward and feedback analysis. For example, in order to analyse the dimensional quality of sheet metal parts, Zhou and Cao [8] measured 28 discrete points with varying inner tonnage, outer tonnage and punch speed. The work has then been extended by Majeske and Hammett [4], where they showed the process variation related to 16 discrete output features (point features) for sheet metal stamping. Further, Zhang, et al. [9] investigated the effect of press tonnage, nitrogen pressure and shut height on waviness of the stamped part.

Further, attempts have been made to predict and control springback errors by adapting neural network training based on finite element simulation or experimental data sets. Cao, et al. [10] developed a springback control system using artificial neural networks to control springback in channel forming process. The proposed numerical simulation results are validated experimentally by Viswanathan, et al. [11]. Liu, et al. [12] predicted springback angle of U-shaped parts under varying process parameters. Few closed-loop variation control strategies have been reported in literature [13]. However, the available neural networks approaches fail for complex part geometry and correlation with overall surface quality is missing. Some work has been also oriented to control stamping process by integrating ANN and FEM as documented in [14].

Recently, multivariate statistical techniques have also been adopted to interpret data and extract significant patterns. In [15] the current state-of-art in multiple fault diagnosis based on data-driven methods (such as Principal component analysis (PCA), correlation clustering, least squares, designed component analysis (DCA) and factor analysis) for sheet metal assembly is presented. While PCA is adapted to reduce the large dimensionality of the original data set (measurements), the decomposed orthogonal principal components may not have a physical interpretation related to faults. On the contrary, DCA requires a previous knowledge of the process in order to construct the fault pattern but it offers a close prediction for fault diagnosis and it is lesser sensitive to measurement noise than PCA.

Unfortunately, there is a lack of proper methodology which can correlate the product and process parameters with the entire surface based geometric errors and it remains unexplored. The following challenges have been identified: (i) unavailability of a parametric approach correlating the measured geometric errors with product and process parameters; (ii) characterisation of the effect of individual process parameters on geometric errors; and, (iii) analytical representation (surrogate model) of the relationship between geometric errors and process parameters.

This paper addresses those challenges by decomposing the captured data into orthogonal error modes and uses the modes as a parametric approach to represent the geometric errors.

The reminder of the paper is organised as follows: Section 2 proposes the methodology, Section 3 demonstrates the methodology with an industrial case study, and Section 4 draws final remarks.

2 METHODOLOGY OVERVIEW

The proposed research methodology is summarised into three major steps as follows:

- *STEP 1* involves the experimental characterisation of the stamping process by varying process parameters. Thereafter, the geometric errors of stamped parts are captured and deviation field is obtained.
- *STEP 2* decomposes the deviation field into orthogonal geometric error modes.
- *STEP 3* develops analytical surrogate model by linking process parameters to decomposed deviation field. The proposed surrogate model can be used to narrow down root causes of failure, usually unforeseen if only based on heuristic approaches.

2.1 *STEP 1*: experimental characterisation

Design of Experiments (DoE) is adopted to characterise the geometric errors under varying process parameter conditions. To capture geometric errors, 3D optical scanner is used which captures millions of data points (Cloud of Points-CoP) representing the entire surface information. To obtain the *deviation field*, the CoP is mapped onto the nominal CAD model. The nominal CAD model is represented through polygonal mesh geometry. Deviation field is calculated for each node of the mesh model, by using the morphing mesh technique, as originally proposed in [16].

The calculated deviation field is non-parametric by nature which cannot be directly linked to process parameters. Therefore, to develop a parametric model of the deviation field, extraction of geometric features from the deviation field is necessary. Assuming m number of mesh node, and p number of DoE experiments, the deviation field (D) can be expressed as in Equation (1), where, $D_{z,j}$ denotes zth node deviation of pth experimental sample.

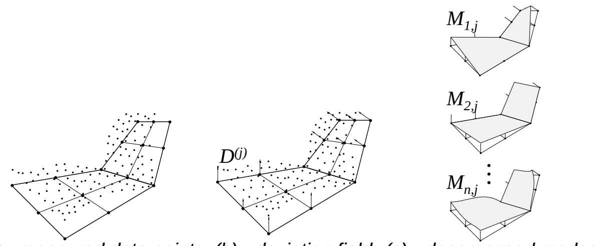
$$D = \{D^{(1)} \quad D^{(2)} \quad \cdots \quad D^{(p)}\};\; D^{(j)} = \{D_{z,j}\}$$
$$\forall z = 1,2,\cdots,m;\; \forall j = 1,2,\cdots,p \tag{1}$$

2.2 *STEP 2*: deviation field decomposition

Past research shows that few attempts have been made to develop parametric model for geometric errors. They can be categorised as *Explicit Parametric Models* (EPM) and *Implicit Parametric Models* (IPM).

The Bezier's surface, non-uniform rational basis spline (NURBS) patches, polynomial surface fitting are few EPMs where the geometric errors are directly controlled by key points [17] [18] [19]. These models fail to represent accurate reconstruction of geometric errors as few control points are insufficient to model complex 3D geometry.

On the contrary, IPMs attempt to decompose the deviation fields into functional parameters. IPM uses various function bases (e.g., signal characterisation techniques) to characterise and decompose the geometric errors into parametric error modes [20] [21] [22]. Till date the developed IPM's methods are mainly limited to geometric error characterisation [23] [24] and to assembly processes [25] [26]. However, there is lack of approaches to link error modes with stamping process parameters.



(a) - measured data points (b) - deviation field (c) - decomposed modes

Figure 2 - Pictorial representation of the deviation field decomposition.

This paper implements Geometric Modal Analysis (GMA) [22] to decompose geometric errors into orthogonal error modes. Decomposed modes can be parameterised by means of its values to represent geometric variation associated with the parts produced through varying process parameters. GMA uses 3D Discrete-Cosine-Transform (3D-DCT) as main kernel to decompose the deviation field into significant error modes. Figure 2 shows the main steps to decompose the deviation fields into significant error modes. Due to orthogonality of the error modes, they can be varied independently to fit different set of geometric errors by changing the amplitude of the modes. A set of decomposed modes for *p* number of experiments is defined as in Equation (2), where *n* is the number of modes. The transformed modes is expressed as a function of the given deviation field, as in Equation (3), where *F* denotes the *decomposition function*.

$$M = \{M^{(1)} \quad M^{(2)} \quad \cdots \quad M^{(p)}\};\; M^{(j)} = \{M_{t,j}\}$$
$$\forall t = 1,2,\cdots,n;\; \forall j = 1,2,\cdots,p \tag{2}$$

$$M_{t,j} = F(D^{(j)}) \tag{3}$$

2.3 *STEP 3*: analytical surrogate model

The parametric nature of decomposed error modes shows clear advantage to link with the stamping process parameters, *SP* (see Equation (4)), where N_{SP} is the total number of process parameters.

To identify the relationship between process parameters and error modes, analytical surrogate model is developed for each error modes.

$$SP = \{SP^{(1)} \quad SP^{(2)} \quad \cdots \quad SP^{(p)}\};\; SP^{(j)} = \{SP_{s,j}\}$$
$$\forall s = 1,2,\cdots,N_{SP};\, \forall j = 1,2,\cdots,p \tag{4}$$

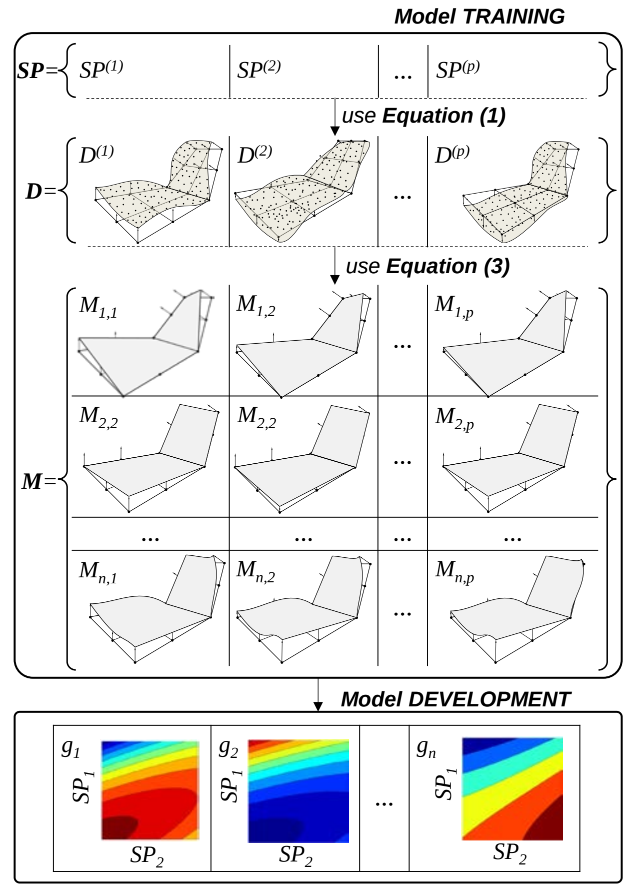


Figure 3 - Pictorial representation of analytical surrogate model development.

The *t*th mode can be expressed as function (g_t) of a set of stamping parameters ($SP^{(j)}$). The analytical function (see Equation (5)), g_t, is computed in two consecutive phases (see Figure 3): (i) model training; and, (ii) model development. *Model TRAINING* uses experimental data from the experimental characterisation (see **STEP 1** of the methodology). *Model DEVELOPMENT* identifies the analytical relationship between process parameters and error modes, as stated in Equation (5). Adaptive polynomial fitting, spline or Kriging methods can be utilized for this purpose [27].

$$M^{(j)} = g_t(SP^{(j)}), \forall t = 1,2,\cdots n \quad (5)$$

$$D^{(j)} = invF(M^{(j)}) \quad (6)$$

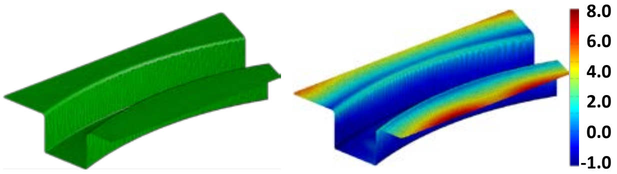
By combining Equation (1) (3) and (5), a parametric relationship can be established between any deviation field and stamping parameters as noted in Equation (6), where, *invF* denotes the *inverse decomposition function*.

3 INDUSTRIAL CASE STUDY

Applicability and effectiveness of the proposed methodology has been demonstrated with an industrial case study. The selected top-hat geometry with nominal polygonal mesh geometry is shown in Figure 4(a). The steps of the methodology are explained as follows:

3.1 *STEP 1*: experimental characterisation

A set of top hat parts has been stamped varying stamping parameters (see Table 1): (i) material thickness (SP_1); (ii) blank holding force (SP_2); (iii) stamping speed (SP_3).



(a) (b)

Figure 4 - (a) Top-hat nominal mesh; (b) Deviation field (mm) computation for run $SP^{(1)}$.

	Experimental Runs (*p*)							
	$SP^{(1)}$	$SP^{(2)}$	$SP^{(3)}$	$SP^{(4)}$	$SP^{(5)}$	$SP^{(6)}$	$SP^{(7)}$	$SP^{(8)}$
Thickness [mm],(SP_1)	0.6	0.6	0.6	0.6	1.2	1.2	1.2	1.2
Holding Force [kN],(SP_2)	150	150	375	375	150	150	375	375
Speed [mm/s], (SP_3)	10	50	10	50	10	50	10	50

Table 1 - Experimental runs with varying process parameters.

Each experimental run has been repeated for 5 times (the average deviation field has been then utilised for further calculations). CoP has been captured using GOM optical scanner (see Figure 5). The deviation field for each experimental treatment has been computed at mesh nodes. For example, Figure 4(b) shows the computed deviation field for experimental run $SP^{(1)}$.

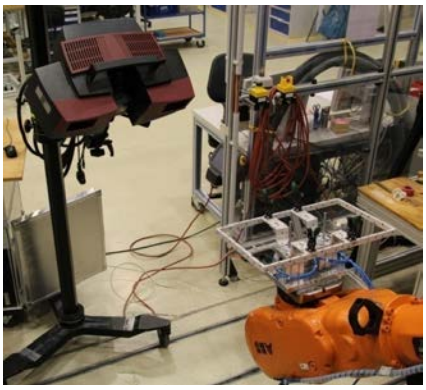


Figure 5 - Experimental setup used to measure CoP of stamped parts.

3.2 *STEP 2*: deviation field decomposition

The obtained deviation field for each experimental run is decomposed using the GMA. Figure 6 shows a sample set of transformed modes, used as parameters to map with process parameters.

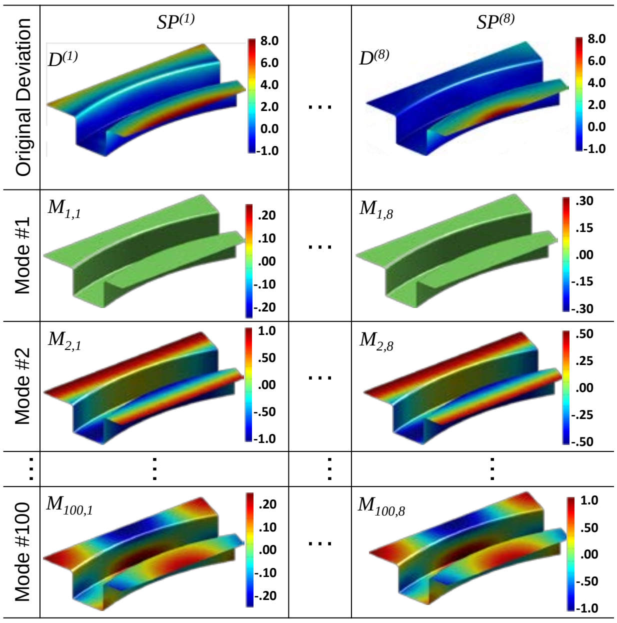


Figure 6 - Deviation field decomposition for each experimental run into error modes.

3.3 *STEP 3*: analytical surrogate model

For each error mode analytical surrogate model has been developed. For this purpose polynomial regression with automatic degree calculation and robust fitting based on automatic cross validation has been implemented. Figure 7 illustrates the parametric surrogate models (contour plots) for modes in relation with varying blank holding force (SP_2) and stamping speed (SP_3).

In order to prove the accuracy of the proposed methodology the original deviation field has been compared against reconstructed surface by using equation (6). Figure 8 shows the results of original deviations, reconstructed deviations and error plot (between original and reconstructed deviations).

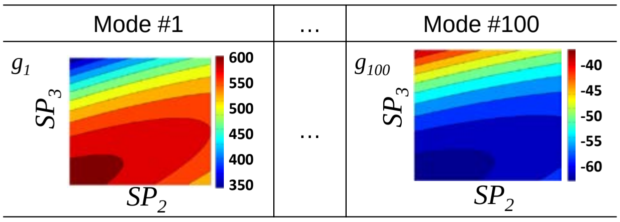


Figure 7 - Surrogate model linking error modes and process parameters (at SP_1=0.6 mm).

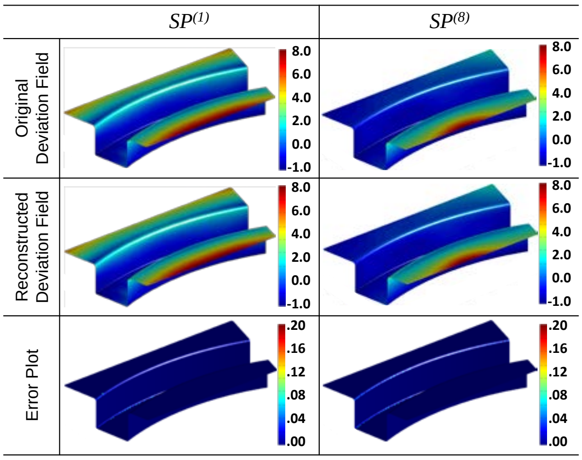


Figure 8 - Original deviation field vs. reconstructed field (deviations in mm).

The proposed methodology is a step forward for predicting geometric errors based on the given set of process parameters (not used during the training step). For example, new parameter set (e.g., thickness, SP_1*= 0.6 mm;* blank holding force, SP_2*= 250 kN;* and, stamping speed, SP_3*= 30 mm/s*) has been selected in between $SP^{(1)}$ and $SP^{(4)}$ to predict the overall geometric deviations [in mm] and is shown in Figure 9.

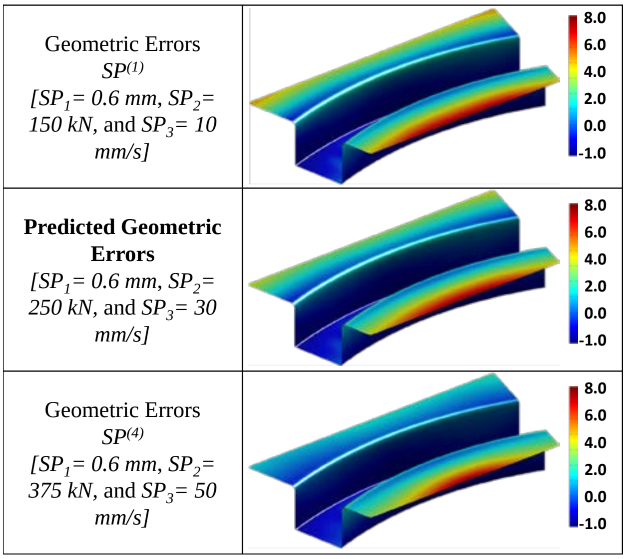


Figure 9 - Prediction of geometric errors for new parameters in between $SP^{(1)}$ and $SP^{(4)}$.

4 CONCLUSION AND FINAL REMARKS

The proposed methodology allows to predict geometric errors by correlating stamping process parameters and monitoring data (such as cloud of points). Geometric errors are defined as deviation field using CoP data which are non-parametric in nature. Therefore, deviation field decomposition has been used to convert CoP data into functional parametric error modes. Subsequently, surrogate model technique has been implemented to link geometric errors and process parameters.

The proposed methodology significantly explores and contributes to the following areas:

- the developed *model-driven* technique represents a step towards automatic closed-loop process control for stamping process;
- costly and time-consuming trial-and-error approaches can be reduced by automatic selection and tuning of process parameters;
- the *model-driven* approach can forecast geometrical variations for given set of process parameters (forward process), and consequently can optimise (feedback process) the process parameters to achieve given quality standards.

Future investigations will be focused on experimental validation of the proposed methodology and root cause identification of global/local geometric errors occurring during production.

5 ACKNOWLEDGMENTS

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7 BIOGRAPHY

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Framework for Developing a Web Based Process Plan for Reconfigurable Press Brake Bending Machine

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Abstract

The increased demand for unpredictable variant sheet metal parts and the need for shorter throughput times and higher quality at minimal prices have placed new requirements on the corresponding process planning systems. This paper involves the formulation of a framework to be used for designing a web based process plan for Reconfigurable Press Brake Bending Machines (RBPM). It proposes to design a framework to represent the real sheet metal bending scenario using IDEFO (Icam DEFinition for Function) modelling. The paper comprises of four major sections: problem formulation, inputs, outputs and model conceptualization. Problem formulation involves identifying variables, setting objectives, determining constraints. The inputs and outputs sections define what the system takes from the user and the results. Model conceptualization involves formulation of algorithms which can simulate the sheet metal bending process. This framework will help to determine the most efficient process plan and identify the feasible bending alternatives.

Keywords

Web based, process planning, bending.

1 INTRODUCTION

Traditional methods of process planning cost companies large amounts such as hardware maintenance costs. A Web-based system to integrate and share engineering information to support design and manufacturing activities such as domain investigation, functional requirement analysis, and system design and modelling was developed [1]. A new design of a reconfigurable bending press machine (RBPM) was proposed, and the design, which is scalable, customizable and flexible, is a means of increasing sheet metal bending productivity [2]. The RBPM design has two major objectives, namely geometric transformation and productivity adjustment. Geometric transformation is achieved through vertical and horizontal configurability, while productivity adjustment is enabled by plug and produce devices. Geometric transformation allows sheet metal benders to adjust the press brake's height and length, thus improving the capability of the RBPMs. This paper presents work in progress for the design of a web based process plan for the reconfigurable bending press machine. This paper seeks to design a framework for developing a web based process plan. In this paper a clear aim and a set of objectives are defined. The paper is structured into four parts, in which the first part is the literature review; it focuses on the review of literature written by other authors which is related to the objectives. Problem formulation is the second part which involves the need to transform these parts into bent parts within the least time and optimal quality. The third part is model conceptualisation which contains the tools for solving the problem. Last of all, functional decomposition which results in three essential modules which are feature recognition, central planning and remote planning.

2 LITERATURE REVIEW

Currently sheet metal processes are considered a viable option, not only for structural components but also for durable consumer goods. Press-Brakes are machines for bending sheet metal [3]. These machines are generally built out of a stationary lower beam and a vertically moving upper beam connected by a frame [4]. Bending is a manufacturing process that produces a V-shape, U-shape, or channel shape along a straight axis in ductile materials, most commonly sheet metal, using standard die sets or bend brakes [5]. Process planning is defined by the society of manufacturing engineers as the 'systematic determination of the methods by which a product is to be manufactured economically and competitively [6]. Computer-Aided Process Planning (CAPP) is the function within a manufacturing facility that establishes the processes and process parameters to be used along with the machines performing those processes, to convert a piece of material from its initial form to a final form which is predetermined on a detailed engineering drawing [7].

The CyberCut system developed at the University of California at Berkeley is a Web-based system integrating product design and process planning as a Java Applet program [8]. The Web-based Distributed Product Realization Environment (Web-

DPR) system was developed as an infrastructure to support collaborative design and manufacturing [9]. A Web-based ERP system for business services and supply chain management: Application to real-world process scheduling was developed [10]. The system's Web-aspect provides significant advantages, as the system is distributed through interoperable, cross-platform and highly pluggable Web-service components.

IDEF0 was developed in order to represent activities or processes (comprising partially ordered sets of activities) that typically are carried out in an organised and standard manner [11]. The IDEF0 definition of a function is ''a set of activities that takes certain inputs and, by means of some mechanism and subject to certain controls, transforms the inputs into outputs''[12]. These inputs, controls, outputs and mechanisms (ICOMs) can be used to model relationships between different activities.

IDEF0 modelling starts by representing the overall purpose of the system and its interfaces with an external environment in a context diagram. This context diagram is hierarchically decomposed into a hierarchy of related diagrams. These IDEF0 diagrams can be further decomposed thereby encoding semantic information at so-called lower levels of modelling [13] as shown in Figure 1 below.

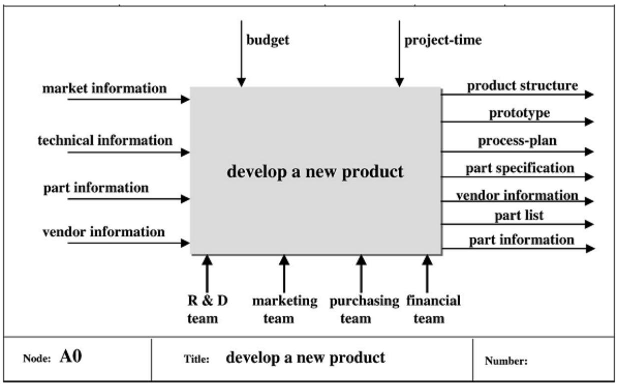

Figure 1 - IDEFO context diagram for the "develop a new product" process [13]

IDEF0 for analysing Web based Distributed Process Planning (Web-DPP) functionalities was adopted [14]. The three core modules of the Web-DPP are modelled in IDEF0 , together with the relationship and data/information flow among the three modules, where M1–M5 represent human, computer, network, security and machine, respectively.

3 PROBLEM FORMULATION

Sheet metal bending involves a substantial number of alternatives which vastly increase with the number of bends in a part. Determining the most efficient process plan therefore becomes complex due to the large search space provided by bending alternatives. To add, not all alternatives are feasible and thus there is need for identifying the feasible ones, in feasible designs.

In the problem addressed by this paper to design a model that allows machine adjustment to suit new production demands. These adjustments include height and length. The need is to transform these parts into bent parts within the least time and optimal quality. There is need for the formulated methodology to classify parts into their respective families and derive the maximum process requirements for each family. The nature of the manufacturing sector for the parts is as follows:

- There is more than one machine capable of performing any operation.
- Each job unit must be completed on a single machine i.e. there is no transfer of work in progress from one machine to another.
- Unless stated otherwise, a batch cannot be split so that unit jobs are done on several machines.
- Each bend can be performed by a single tool and a single tool can perform several bends.
- Each machine configuration can be altered (change of setup) to suit requirements of any part.

3.1 Model Conceptualization

Using the IDEFO modelling technique, the system can be represented with inputs, outputs, tools and constraints. The tools for solving the problem may be as follows:

Computer Aided Design (CAD) software, for manipulating the part model as desired. **Computer Aided Manufacturing** (***CAM) software*** manipulates the instructions (G- Code) and physical entities. G-code is a numerical control (NC) programming language used in computer-aided manufacturing for controlling automated machine tools.

Databases (DB) store recurring information and allow for quick and easy retrieval. ***Mathematical models (MM)*** optimize the system.

Custom programs (CP) do monitor all other entities as well as perform other functions to produce a process plan. ***The operator (OP)*** is responsible for handling other cases which may require human intervention.

The constraints are those variables which govern the output of the system but are not changed by it. Standards govern the level of quality of the output and cannot be changed by the system. Production plans set out information about all the stages of production, so that all outputs are made to the same quality.

A context diagram to represent the whole system is shown in Figure 2.

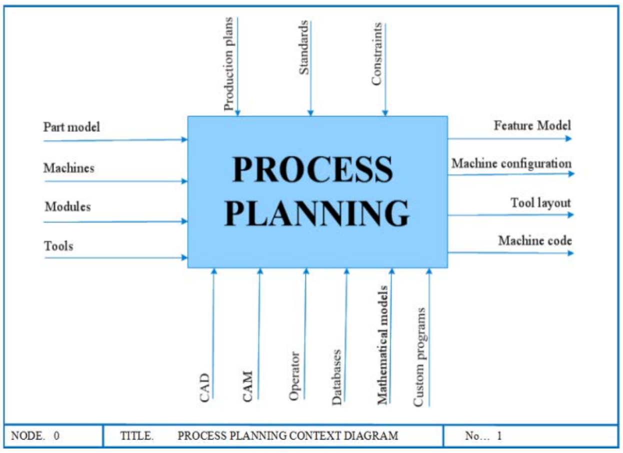

Figure 2 - Context diagram for Distributed CAPP Functional Decomposition

3.2 The Top Down Aproach

The top-down approach is used in decomposing the problem, starting with a context diagram going downwards. The IDEF0 modelling is a top down approach. The top down approach allows the design and improvement of the system. It exposes one new detail at a time beginning at the highest level by modelling the system as a whole. The bottom up approach cannot be used because it involves a risk that changes made will not always work. Decomposing the process planning problem results in three essential modules which are feature recognition, central planning and remote planning, as shown in Figure 3.

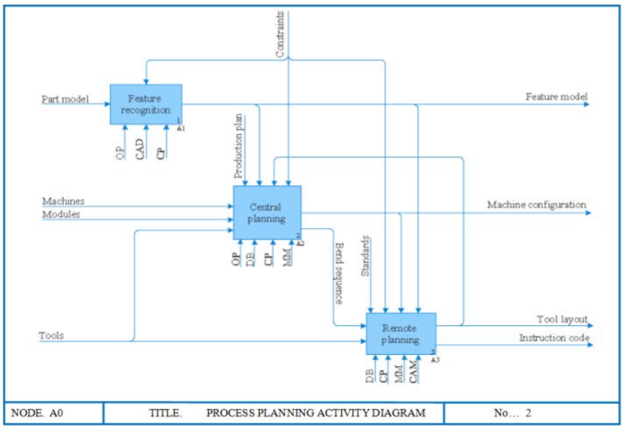

Figure 3 - Process planning activity diagram

3.3 Feature Recognition

Feature recognition is the process of transforming a CAD model into a feature model with manufacturing information attached to it. At this stage the operator, CAD software packages and custom programs are the tools used for this transformation. Constraint rules govern the determination of features.

Feature recognition can be further decomposed into manageable modules, which are Translate model, surface feature recognition, relate surfaces, extract features and validate features. These modules work hand in hand with each other to determine bending features and working parameters from CAD geometry, tolerances and the type of material employed. The activity diagram for feature recognition is shown in Figure 4.

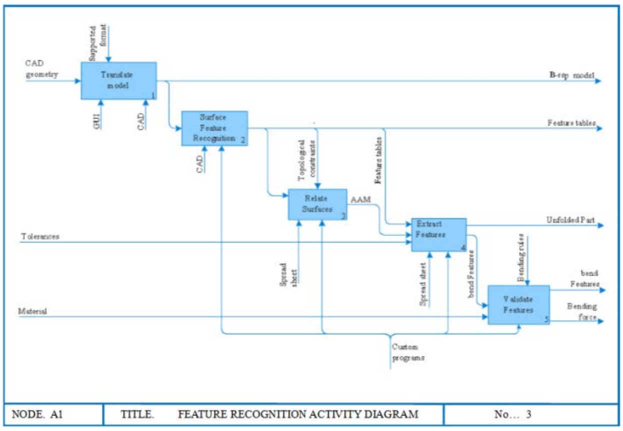

Figure 4 - Feature recognition activity diagram

3.4 Translation model

This module transforms a CAD file into a b-rep model, which can be used as input to the next module. The system accepts a CAD model in any of the specified formats. Only a few format scan be used such as STEP (Standard for the Exchange of Product model data) and IGES (Initial Graphics Exchange Specification) can be decoded without the use of CAD software. To translate a model, importation of add-ins in inventor will be used. The add-ins are accessed by a unique identifier. For each file format is an add-in for translating a related file into a b-rep representation. Importing is the name given to the translation process. Files can be imported using default settings (options set for the previous translation), or specified in a program. For convenience, this module will specify the most important options. The b-rep features are specified by the three options ImportSurface, ImportSOLID and ImportWire. These are the settings to be considered in this research. The module execution flow chart is shown in Figure 5

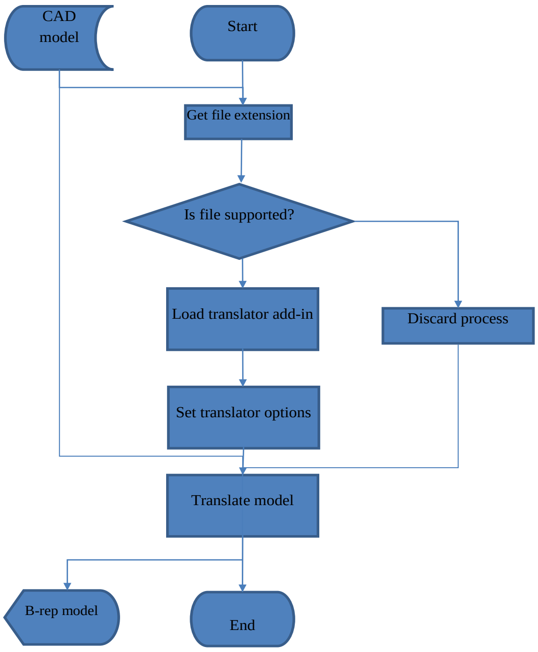

Figure 5 - Translation model

3.5 Surface Feature Recognition

The surface feature recognition model extracts b-rep data from the translated b-rep model into feature tables using an object oriented approach. The following objects will be used:

- A surface body object which represents a discrete part made up of joined faces.
- A face object represents the surfaces that make up a discrete part. The surface is bound by a set of interconnected edges.
- An edge object which represents each line in a set of lines which make up the boundary of a face. An edge consists of three vertices or points on the edge.

A table is a matrix made up of rows, columns and cells. The pseudo-code for this extraction is as follows:

Program Name: **BREP DATA EXTRACTION**
Declaration of Variables:
Declare oSurfaceBody as SurfaceBody object.

Declare oFace as Face object

Declare oEdge as Edge object

Start:

For each oSurfaceBody

Create a new worksheet

For each oFace in the surfacebody

Create a table

Set Table title to face name value

For each oEdge in a face

Add a new row in the table

Get the edge ID into first column of table

Get the edge type into second column of table

Get the edge start vertex into third column of table

Get the edge midpoint vertex into fourth column of table

Get the edge end vertex into fifth column of table

Next oEdge

Next oFace

Next oSurfaceBody

End.

3.6 Relate Surfaces

Using data from the feature tables, this module identifies the relationship between faces and edges. Two types of relationships are to be presented viz. the relationship between two edges which belong to the same face and the relationship between two adjacent faces.

The relationship between two edges are characterized by:

- 0, if edges of the same four sided face are adjacent.
- 1, otherwise. These edges will be opposite to each other.

The pseudo-code to determine if a face is four-edged is as simple as counting the number of rows in the representing table. If the number of rows is 4 then the face is four-edged. For testing adjacency, the vertices between edges are compared. If any of the edges are identical then the relationship is 0, otherwise it is 1.

The relationship between faces is characterized as follows:

- 0, if the faces are adjacent i.e. share a common edge.
- 1, otherwise.

This relationship is tested by checking a common edge between faces. This is achieved by combining the data into one table and sorting by edge ascending order and extracting the face data with the common edges as they precede each other in this order.

3.7 Extract Features

The edges relationship matrix can be used to eliminate thickness faces, remaining with working faces only. All four-edged faces form a loop joined together by common edges. A thickness face is determined by the following rules:

- The face must contain exactly four edges.
- All thickness faces joined together form a loop.
- All common edges within the loop must be equal.
- All common edges within the loop must be of the smallest dimension among several loops.

The loops are traversed from the edge matrix. The flow chart for getting a loop is represented in Figure 6.

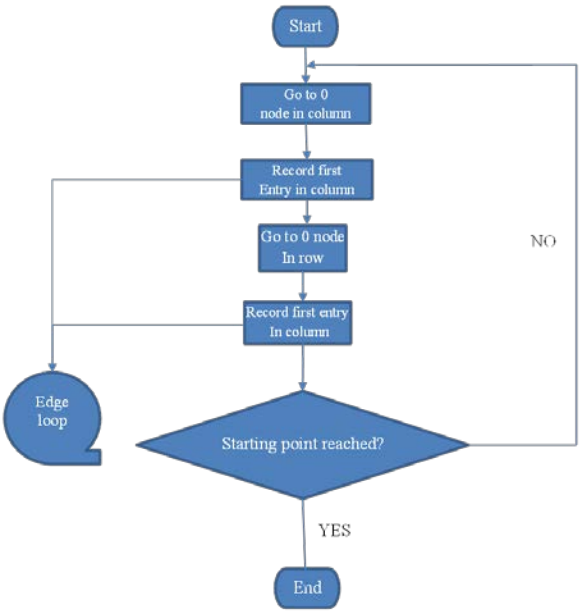

Figure 6 - Extracting Features

The outcome of eliminating the edge loops is two discrete sets of surfaces, which are equally offset. One of these surfaces must be eliminated to remain with a single layer representation of the sheet metal part. This elimination gives rise to the bend allowance error, which must be compensated. For this reason, a bend feature specifying whether the radius is internal or external is attached. All adjacent faces represent a bent feature.

3.8 Validate Features

Validation of a feature involves calculating the minimum radius for each bend.

4 CENTRAL PLANNING

Central planning involves generating a generalized plan, which is not specific to any machine. It involves tool selection, bending sequencing, and machine selection. The diagram below shows that the bending features determine the tools to be used. The IDEF0 diagram for central planning is shown in Figure 7.

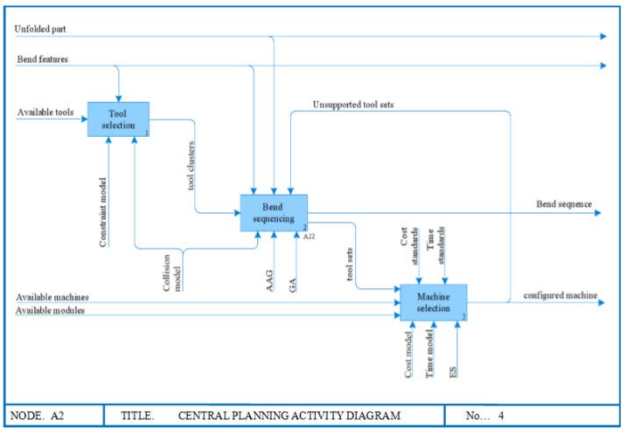

Figure 7 - The central planning activity diagram

4.1 Tool Selection

The tool selection module selects all tools which are suitable for producing a bend. The tools are grouped into clusters according to the bends they can produce. For example, cluster A contains all tools suitable for producing bend A. This module requires for each bend: bend radius, length and angle as input. Tools are selected starting with the longest bend in descending order. A tool selection criterion for each bend feature is as follows:

- Tool radius must exactly match the bend radius within tolerances.
- Tool angle must be equal to or less than bend angle.
- Tool length must be equal to bend length, or greater than the bend length if the tool is already selected.

4.2 Bend sequencing

Bend sequencing is the process of generating the pattern to be followed to produce the part. This module can be broken down into two sections which are determined feasible sequences and heuristic search.

4.3 Machine selection

The machine selection module involves selecting a machine which:

- Has length adjustment capabilities
- Has height adjustment capabilities
- Is capable of delivering the required bending force.
- Will complete the job in the earliest possible date.
- Will deliver the job at the most optimum cost.

4.4 Remote Planning

The remote planning involves transforming the high-level process plan from central planning into a plan suitable for the selected machine. The output is the final plan ready for shop floor processing. It involves specifying:

- Machine
- Height
- Angle of bent
- length
- Number of tools involved.
- tool order
- bend sequence
- Bending force
- Bending time
- Size of raw sheet
- Cost of bending

The cost is the sum of hourly rate, power consumption and raw work piece.

5 CONCLUSIONS

In this paper a concept for meeting the process planning needs was formulated. The process started by defining the inputs and outputs of the system were clearly defined. A system model concept for solving the mathematical model using the stated inputs to produce desired outputs was then described. This included three sections which are feature recognition, central planning and remote planning. This is the first model to be designed for RBPMs. Most models available are for turning and milling. This system model allows the design and improvement of the system. It exposes one new detail at a time beginning at the highest level by modelling the system as a whole. The model helps organise the analysis of the system.

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8 BIOGRAPHY

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Additive Manufacturing for Improved Al- and Mg-Parts

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Abstract
80 % of the non-ferrous casting in Germany is aluminium casting. In comparison to aluminium, the specific weight of the light weight metal magnesium is only two third of aluminium and does not suffer from the shortage of resources. The process efficiency and the resulting material properties of the products are determined by the cooling principle of the tool. Additive manufacturing has been not yet established in broad application for the pressure die casting process. The favourite principle selective laser melting is still on the edge of a breakthrough in the tooling industry. Own material tests showed a lower breaking elongation. Also the resulting notch impact energy is lower. The demand of the industry to accept additive manufactured tool inserts are therefore better material properties, the possibility of using the hot working steel X38CrMoV5-1 (1.2343) and a lower price.

Keywords
Rapid Prototyping, Rapid Manufacturing, Pressure Die Casting Moulds, Conformal Cooling

1 INTRODUCTION

The high thermo-mechanical alternating load limits the tool life of die casting moulds. The quality of the parts can be reduced by insufficient inhomogeneous heat dissipation. Using drilled boreholes, no homogeneous heat dissipation from all areas of the mould is possible. The cooling of different areas according to their specific need of heating and cooling is very difficult with straight boreholes. Therefore, surface spray cooling is necessary for a sufficient cooling and widely-used. The spray cooling limits the tool life and reduces the quality of the die parts. To overcome these disadvantages, a new tool concept with conformal cooling shall be realised [6]. First experiences for conformal cooled moulds were done by the manufacturing technology selective laser melting [6]. After the experience with selective laser melting concerning another reference object (gear housing), which is described in [4], alternative concepts with lower costs and better material properties were required. To realise a conformal cooling system, manufacturing solutions are needed, which can meet these requirements.

Two alternative concepts were investigated. The objectives of the new process under the conditions of conformal cooling are summarised in Table 1. Especially different wall thicknesses in the part result in inhomogeneous temperatures. This leads to a higher surface cooling by spraying and crack initiation. These aspects shell be improved by conformal cooling.

In the first example, the cooling system was realised by using conventional manufacturing processes. For an aluminium pressure die casting reference tool, the conformal cooling system was milled in the back of the inserts and welded with suitable cores. With this technology, inserts of the favourite material X38CrMoV5-1 and a lower price can be realised.

Old process	New process
Inhomogeneous cooling by straight drilled boreholes	Homogeneous cooling by contour following cooling channels
Higher surface spray cooling necessary	Reduced surface spray cooling by improved internal cooling system
Lower cooling rates of the internal cooling system	Higher cooling rates of the internal cooling system
Higher thermo-shock through spray cooling	Reduced crack initiation by reduced spray cooling and thermo-shock
Larger grain size, more porosity	Finer grain size, less porosity

Table 1 - Objectives for new processes

By using additive manufacturing in the current project, the focus is on the Metal Powder Application process (“Metal Powder Application”, MPA), which is actually a cold spray technology. Its building rate is 18 times higher than with selective laser melting, the price is lower and the wanted hot working steels, even in combination with copper, can be used [2].

First approaches for the improvement of the sophisticated pressure die casting can be supported by suitable technical tools and methodical aids. For the determination of the problem, available possibilities are given with thermographic devices and specific simulation software. The first step is the analysis of the initial state with the help of casting simulations, thermographs and additional metallographic specimens. This is the basis for developing the new cooling system. The next step comprises the new design evaluated by casting simulations, fluid dynamics and strength calculations as well as thermal simulations in comparison with the initial state. After the practical realisation of the new design, casting tests are carried out to prove the effects of the new cooling system.

2 ALUMIMIUM PRESSURE DIE CASTING

2.1 Initial State

For the investigations, an available tool of an engine bracket was used. The part is shown in Figure 1. The cooling systems in the die inserts were realised by drilled boreholes. In the slide, dead end holes with a tape or copper inserts were installed.

This cooling system is shown in Figure 2. For this tool, a casting simulation was carried out. Here, hot spots were detected in the thicker areas of the part as shown in Figure 3. The aim of the new cooling system is to improve the cooling rates of these areas.

Figure 1 - Engine bracket.

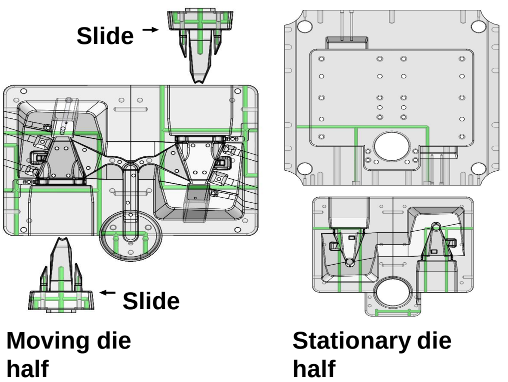

Figure 2 - Cooling system, initial state.

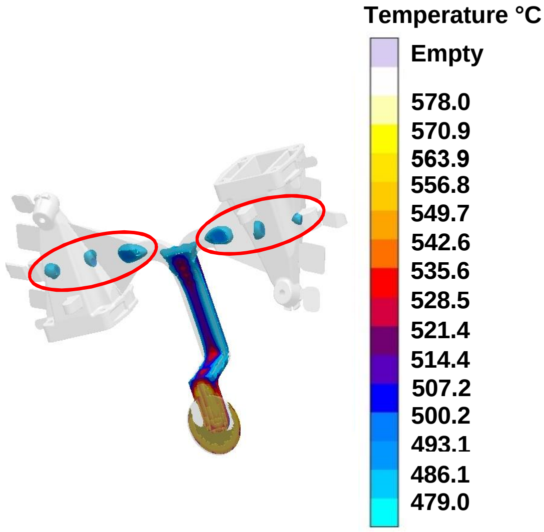

Figure 3 - Casting simulation of engine bracket, region of interest marked.

2.2 Test Rig

All investigations were carried out on the moving die half. The camera was installed on an attachment, which was fixed on the pressure die casting machine. So, shock free picture sequences could be taken. The pictures were taken after ejection of the die casting part. The measurements were triggered by a time schedule. A FLIR SC660 camera with the software ThermaCAM^{TM} Researcher^{TM} was used. The test rig is shown in Figure 4.

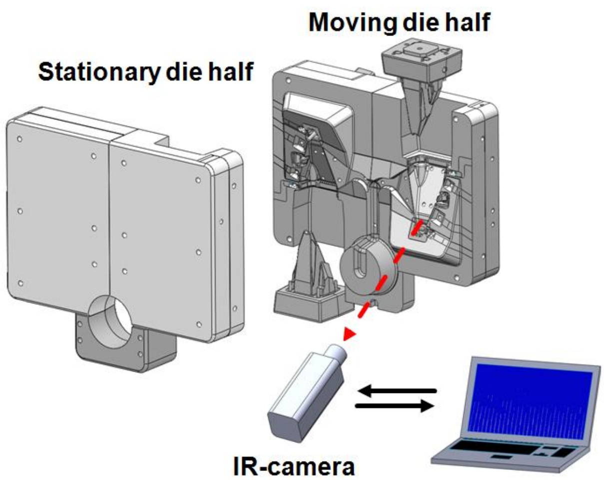

Figure 4 - Experimental setup.

To validate the thermographs, two thermo sensors were installed. The first one is placed in the slide. The second one is positioned on the opposite of the first one in the stationary die half.

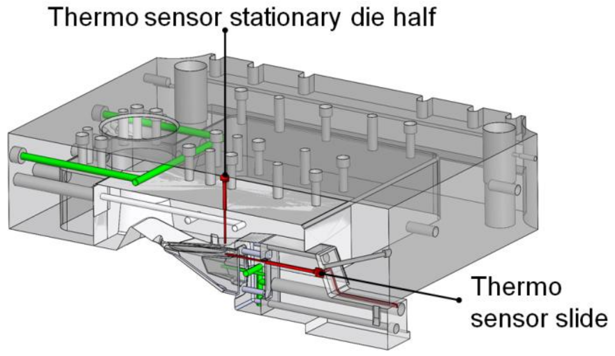

Figure 5 - Position of thermo sensors.

Process:

- Engine bracket, weight: 4008 g
- Alloy: AlSi9Cu3 (Fe)
- Mould filling time: 0.064 s
- Intensifier pressure: 5 s and 820 bar
- Opening of the mould: 12 s
- Ejection of the die part: 15 s, start of infrared thermography
- Application of releasing agent, closing of the mould: 87 s

Test Conditions:

- Bühler SCD/84 die casting machine, 8400 kN locking force
- Impulse cooling unit (ONI Temperiertechnik Rhytemper GmbH) only used for data analysis of the thermo sensors

2.3 Casting Test Results – Initial State

In Figure 6 a thermograph of the mould in the image subtraction mode can be seen. A series of pictures is taken and the temperatures of the pictures are subtracted. To obtain the cooling rates, temperature differences are calculated. The numbered measuring points (AR01-AR04) to determine the cooling rates can be seen in Figure 6. The cooling rates for both slides and die inserts are the same, see Table 2 (slide 0.5 K/s, die insert 1.9 K/s). The investigations of the initial state show that, with the cooling system, the mould temperature can be kept constant. At the same time this is the potential for the new cooling system. The cooling rates, especially for the slides, should be increased. The main part of the heat must be transferred by the slides, because during solidification the die part shrinks to them.

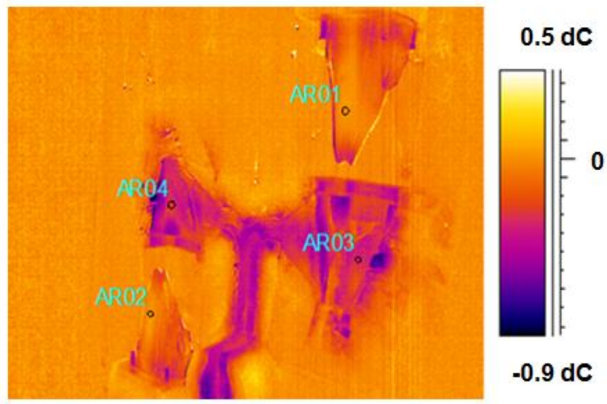

Figure 6 - Thermograph of the mould

Mode	No.	Cooling rate	
		Slide [K/s]	Die insert [K/s]
Image subtraction	1	0.55	2.1
	2	0.4	1.5
	3	0.5	1.9
	4	0.5	1.9
	5	0.5	1.9
Average cooling rate		**0.5**	**1.9**

Table 2 - Cooling rates

2.4 New Design

Based on the negative experiences with selective laser melting concerning the resulting material properties of 1.2709 (X3NiCoMoTi18-9-5), alternative possibilities for realising a conformal cooling system were needed [4]. It was focused on conventional manufacturing technologies. Therefore it was decided to mill the new cooling system in the back of the slides and die inserts. Suitable cores were welded into these gaps to realise conformal cooling channels with equal cross sections. The principle is presented in Figure 7. The risk of tension cracks during welding or the die casting process respectively is given, which is a compromise of this design.

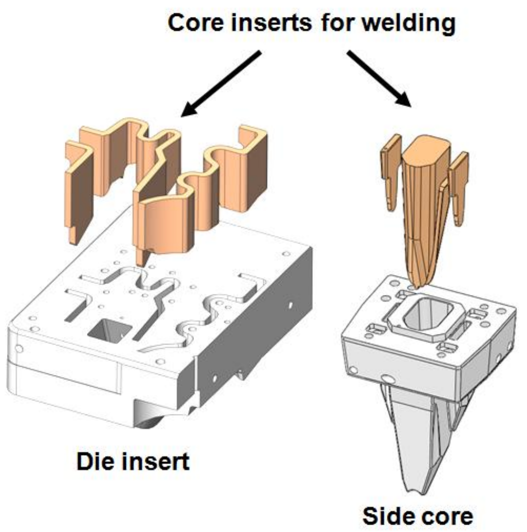

Figure 7 - New design.

The new cooling channel layouts are shown in Figure 9 and 10. Instead of one cooling system in the slide and copper inserts, two cooling systems are realised. The first one is placed in the middle contour and the second one cools both side contours. For the new die insert, three cooling systems were installed comparing to one system in the initial state.

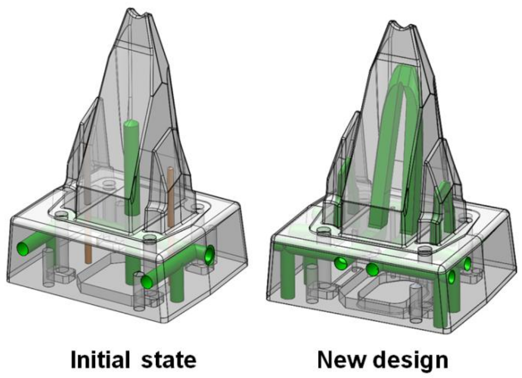

Figure 8 - Cooling system - slide.

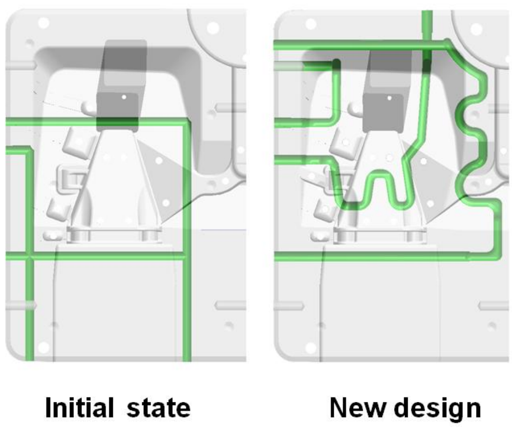

Figure 9 - Cooling system - die insert

Based on hot spots in the thicker areas of the die part, the new cooling system was designed for a better cooling effect in these areas. According to performed die casting simulations and computational fluid dynamics, these effects, were proved. The steady state strength calculation at room temperature showed a higher deformation where the conformal cooling is situated. Investigations on a new channel design for a die insert of an aluminium gear housing die part (not shown here) proved that tensions on the surface can be reduced. In dependence of the channel geometry lower but also higher tensions can be detected. The tensions are nearer to the surface according to the position of the new cooling system. Casting simulations on the gear housing mould showed that a nearer distance to the surface with smaller diameter has a tendency of lower tensions on the channel surface. But for this concept the calculated heat flow rate was lower compared to bigger channels. Simultaneously the fluid temperature of the channel system increases more. An overview about all performed simulations of the engine bracket is shown in Figure 8.

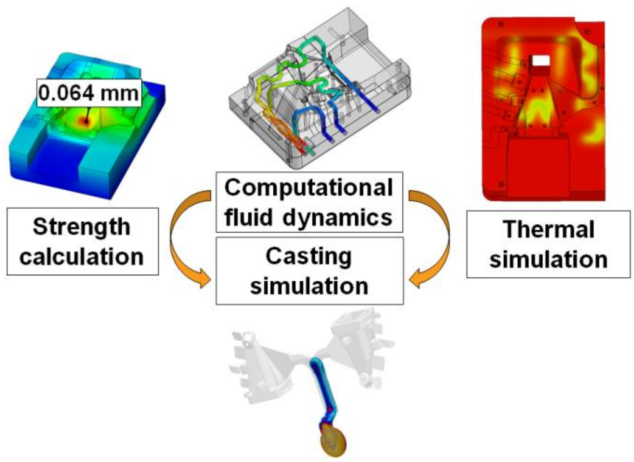

Figure 10 - Performed simulation.

With the new cooling system, heat flow rates that are 4 times higher for the slide and 3 times higher for the die insert were calculated. As investigations have shown, the volume flow rate should be as high as possible for a good efficiency of the cooling system. Several cooling system versions were developed. In accordance with all partners, it was decided not to reduce the channel diameters or to parallelise the cooling channels. Therefore the channel diameters of the initial state were the same for the new design. The distance to the surface is 7-10 mm. Strength calculations indicated that the deformation nearly doubles for the new design of the die insert. Thermal simulations showed that for a homogeneous surface temperature the whole insert would need a network of cooling channels. All channels should have an equal distance to the surface and to each other. Unfortunately the effort to manufacture the components and the resulting strength of such a design are against a network of cooling channels. The casting simulation showed hot spots in thicker areas of the die part, which solidified 4 s earlier than in the initial state. The casting simulation refers to a theoretical concept, where all tool components were equipped with a conformal cooling system. Furthermore an extremely high heat transfer coefficient of 10.000 $W/m^2 \cdot K$ was assumed. For financial reasons, only one slide and die insert were manufactured with milling.

3 MAGNESIUM PRESSURE DIE CASTING

3.1 Initial State

Because of its ideal properties as material for lightweight design, a rising demand is assumed for the next years [1], [5]. Therefore conformal cooling in magnesium die casting is a valuable contribution to the product and process efficiency.

As reference die part, an electronic housing from the automotive industry of AZ91 (MgAl9Zn1) was chosen. The die part is shown in Figure 11.

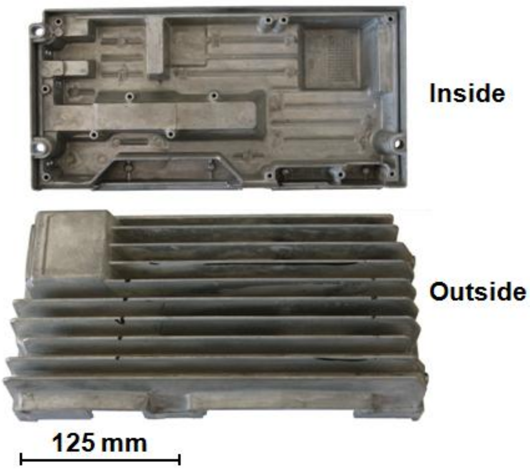

Figure 11 - Electronic housing AZ91 (MgAl9Zn1).

In Figure 12 the cooling system of the initial state is shown. Both die halves have drilled boreholes. The region of interest is shown in Figure 13. The casting simulation showed that the solidification of the highest cooling fins of the electronic housing occurs at the end. Here, cracks occur very early in the tool, because of the high temperature in these areas. Therefore a better cooling of the fins is necessary.

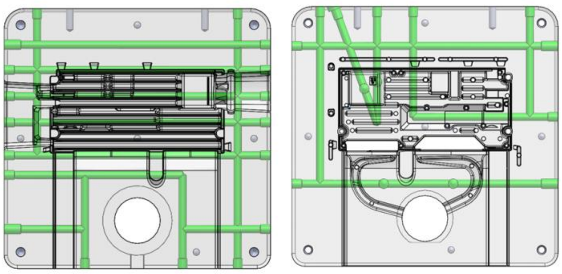

Figure 12 - Initial state cooling system.

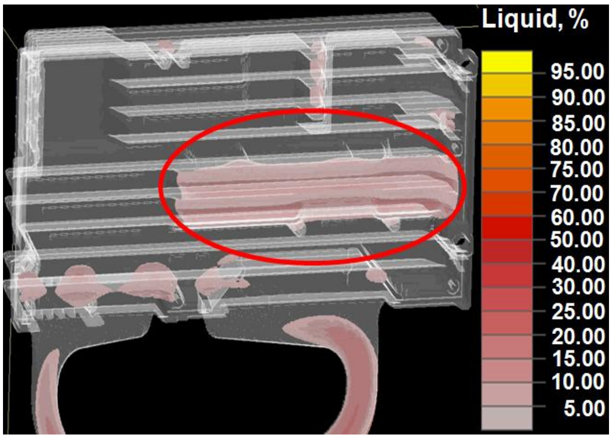

Figure 13 - Casting simulation, region of interest marked.

3.2 Metal Powder Application (MPA)

The MPA process, as shown in Figure 14, was developed over years by the company Hermle Maschinenbau GmbH in Ottobrunn, Germany. It is actually a cold spray technology. Metal powder is accelerated by water steam through a laval nozzle and impinges on the surface of a metal substrate. The kinetic energy of the impact is used to forge metal powder particles together. Different hot working steel powders like 1.2344 (X40CrMoV5-1) as well as 1.2367 (X38CrMoV5-3), copper and combinations of steel can be used. The whole process is integrated into a 5 axis CNC milling system. A following heat treatment at 1000 °C is necessary to obtain the final strength. Using a water-soluble filler material, also interior structures like cooling channels and undercuts are possible to fabricate [2].

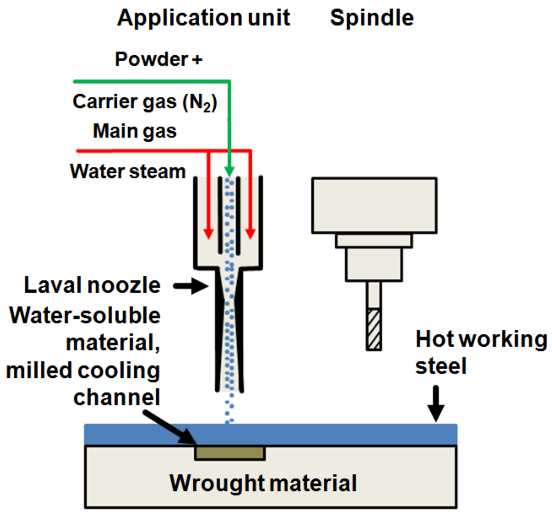

Figure 14 - Principle Metal Powder Application (MPA) [1].

3.3 Goal

For a further improvement of the cooling effect and to minimize the risk of cracks in the mould, especially for magnesium pressure die casting, the new principle for realising a conformal cooling was investigated. Therefore a window for the core with the new cooling system is cut into the die insert. In this window a core is put in, which is manufactured by Metal Powder Application with hot working steel (1.2344) together with copper for a better thermal conduction. The copper is necessary, because the fins are too small for installing cooling channels. The new core design with cooling channels and copper inserts is shown in Figure 15.

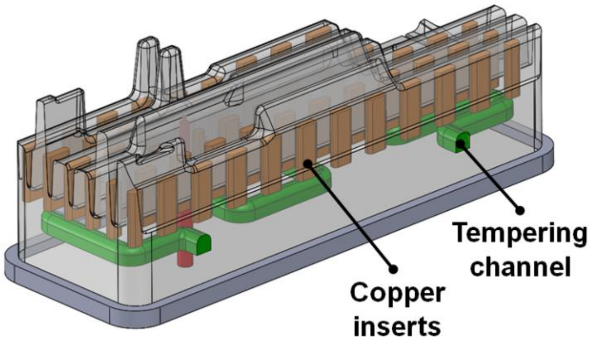

Figure 15 - New cooling channel layout with copper inserts built with MPA.

4 SUMMARY

This paper presents the development by using selective laser melting as additive manufacturing process to fabricate die inserts, switching to conventional technologies and a cold gas spray technology to obtain better material properties and a lower price.

According to computational fluid dynamics, a 3-4 times higher heat flow rate can be realised for the engine bracket. Simultaneously the deformation nearly doubles. The better heat flow rate was also proved by casting tests concerning the gear housing. The casting tests for the new design of the engine bracket as well as for the initial state and the new cooling channel layout of the electronic housing are not yet carried out.

5 ACKNOWLEDGMENTS

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Federal Ministry of Education and Research

Federal Ministry of Economics and Technology

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7 BIOGRAPHY

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Direct Metal Laser Sintering of Ti6Al4V (ELI) Powder

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Abstract
Direct metal laser sintering (DMLS) is an innovative technology which allows the production of fully dense objects or fine-structured parts with complex shapes. Ti6Al4V (ELI) alloy is typically used for biomedical implants, aerospace components and cryogenic applications. Stability and certification of the properties of DMLS objects is an important task for all producers and end-users. Drawbacks of this technology are high residual stress in as-made DMLS objects and anisotropy of mechanical properties. Final mechanical properties of the SLM object depend on the thermal history of the bulk material that was subjected to previous heating and cooling cycles many times during the multipass laser treatment. Numerical simulation allows estimation of temperature distribution and stresses during DMLS of Ti6Al4V (ELI).

Keywords
Direct metal laser sintering, Residual stress, Mechanical properties, Titanium powders

1 INTRODUCTION

Direct Metal Laser Sintering (DMLS) is an additive manufacturing technology which produces parts from metal powder deposited in a thin layer utilizing laser beam scanning. The powder material absorbed energy from the laser and melts. The laser beam scans over the powder thus melting the powder particles and also the previous layer. Sequentially, track by track, layer by layer, a 3D DMLS object is created. Parts with complex inner structures are in demand for automotive, aerospace and medical industries. Temperature gradients play a key role in the genesis of the residual stresses in DMLS objects. Residual stresses in as-built DMLS parts are tensile and high [Shiomi et al., 2004; Merselis and Kruth, 2006; Furumoto et al.., 2010; Yadroitsava et al., 2014; Yadroitsev et al., 2015]. The Centre for Rapid Prototyping and Manufacturing at the Central University of Technology, Free State specializes in producing medical implants from Ti6Al4V (ELI), thus knowledge about properties of DMLS samples is of primary importance for the manufacturing of reliable implants.

2 MATERIALS AND METHODS

2.1 Manufacturing of Ti6Al4V (ELI) samples

Ti6Al4V alloy is a low density, high strength-to-weight ratio, extraordinary corrosion resistant material and it is biocompatible. Ti6Al4V alloy is an α/β titanium being a heat treatable alloy which makes it more attractive due to the versatility it offers [Donachie, 2000]. The Ti6Al4V (ELI) powder used was pre-alloyed gas atomized powder. The chemical composition was as follows: Ti – balance, Al – 6.31%, V –4.09%, O – 0.12%, N – 0.009%, H – 0.003%, Fe – 0.20%, C – 0.005% (weight %). The equivalent diameters (weighted by volume) of the powder particles were d_{10} = 13 µm, d_{50} = 23 µm and d_{90} = 37 µm. Ti6Al4V samples were produced by the EOSINT M280 system. A back-and-forth scanning by strips with the hatch distance of 100 µm was applied for manufacturing specimens. The substrate and powder materials were similar in chemical composition. Argon was used as the protective atmosphere.

2.2 Numerical simulation of laser melting of Ti6Al4V alloy

When the laser beam scans the surface of the solid sample, the evolution of the temperature due to heat conduction can be estimated from (1):

$$\rho c_p \frac{\partial T}{\partial t} - \nabla(k\nabla T) = Q \qquad (1)$$

T is the temperature, t is the time, ρ is the density of material, c_p is the specific heat capacity, k is the thermal conductivity, Q is the source term, i.e. power absorbed from the laser beam. The laser beam intensity had a Gaussian profile. Equation (1) takes into consideration only the effect of conduction into a solid [Sanders, 1984]. For numerical simulations, properties of Ti6Al4V are temperature-dependent [Mills, 2002; Boivineau et al., 2006; Hodge et al., 2014]. Temperature-dependent specific c_p heat capacity was selected with respect to latent heat of fusion.

Marangoni flow which occurs due to a local difference in the surface tension of the liquid, can contribute significantly to temperature distribution and the shape of molten pool [Davis, 1987; Edwards et al., 1991; Sternling et al., 1959; Limmaneevichitr and Kou, 2000]. Effective thermal conductivity of the liquid metal has been introduced by Kim et al. 2003, Zhang et al. 2004, He et al., 2003 for taking into account changing in heat balance due to flows. For Ti6Al4V alloy the effective thermal conductivity of the liquid metal was introduced as a value multiplied by a factor of 1.5-3. Except for the top surface, all other boundaries are assumed to be thermally insulated. The heat flux on the top surface simulates convective cooling (Eq. 2). Heat losses due to convection is expressed by

$$Q_c=h_c(T-T_o) \quad (2)$$

where T_0=293 K is initial temperature, h_c = 10 W/(m^{2}K) is convection coefficient.

To validate the model, the actual experimental true temperatures from Yadroitsev et al. (2014) were used as input for the simulation. 4 scan lines were simulated. 3D numerical simulation of the laser processing was carried out using the COMSOL 5.1 (COMSOL, Inc.) a heat transfer module. In order to obtain accurate results, the density of the mesh in the region around the irradiation, and on the top region of the sample (100 µm), was higher than in the sample as a whole, the minimal mesh size was 0.1 µm.

2.3 Residual stress measurements

The residual stress measurements were done with an X-ray diffractometer from ProtoXRD. The residual stresses were determined using the sin2 ψ method. The lattice deformations of the Ti-α were determined using a CuKα radiation source. Scans were performed around a {213} Bragg diffraction peak (2θ~139.69°) at 9 tilting angles ψ between –44.16+44.16°. The residual stresses were calculated considering plane stress conditions using X-ray elastic constants: -S_1= 2.83×10^{-6}MPa^{-1}; ½ S_2=11.89×10^{-6} MPa^{-1}.The electrolytic removal technique was used to determine in-depth residual stress distribution. Since the rotation of the scanning direction is the standard strategy incorporated by the EOS machine, principal stresses and their directions were analysed.

2.4 Roughness measurements

At prescribed Ti6Al4V process-parameters, the last layers of the parts are rescanned twice, without stripes, at 90° for each layer ("upskin" regime). Figure 1 presents typical view of the top surface of the DMLS specimens.

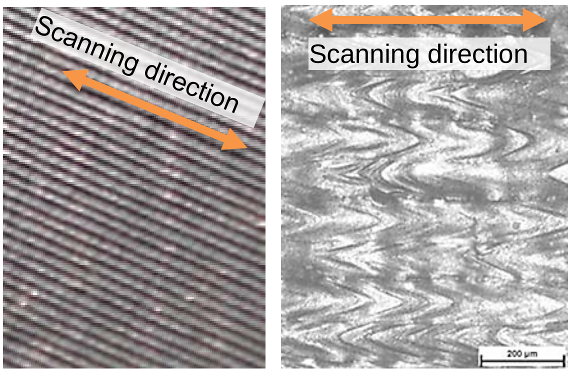


Figure 1 - Top surface of the samples

Roughness was measured in perpendicular directions by a surface roughness tester Mitutoyo SJ-210 (ISO 1997).

3 RESULTS AND DISCUSSION

DMLS samples were produced at process-parameters and the strategy recommended by EOS for the M280 machine for Ti6Al4V powder. Layer thickness was 30 µm. Ten samples 10×10 mm with prescribed thickness 0 (without powder), 1, 5, 10, 15 up to 40 layers and cubes 10×10×10 mm with/without support structures were manufactured and analysed.

Figure 2 shows the variation in average surface roughness with powder layer. After laser scanning of the smooth substrate, which has *Ra*=0.7±0.32 µm and *Rz*=4.0±1.83 µm, the roughness slightly increased. Delivering and laser scanning of the first layer significantly increases the surface roughness of the synthesized layer. Delivering of the first powder layer has some peculiarities: plate curvature (if existed), bias in mounting base plate (substrate) parallel to the horizontal level influence on the amount of the powder involved in synthesizing tracks of the first layer. With the delivering of subsequent layers the situation improves and from the 10th layer upwards the roughness is practically constant and its average was *Ra*=4.3±0.77 µm and *Rz*=22.1±3.79 µm.

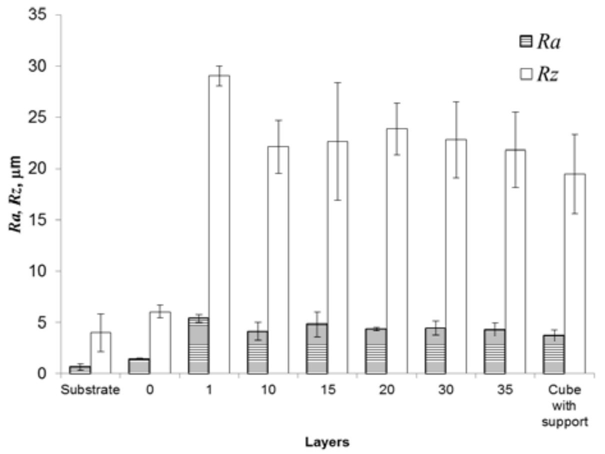


Figure 2 - Roughness of the DMLS samples

Figure 3 shows optical microscope photo of etched as-built Ti6Al4V specimen. A received martensitic α' microstructure is typical for Ti6Al4V samples manufactured by DMLS. In the built direction columnar growth is observed. The microstructure of the DMLS samples differs from the microstructure of wrought Ti6Al4V alloy since the cooling rates during DMLS reach 10^5–10^6 K/s [Rafi et al., 2013].

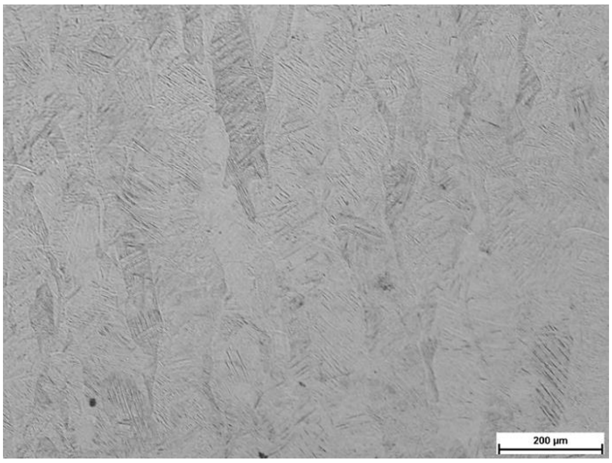


Figure 3 - Microstructure of as-built DMLS sample

Temperatures during back-and-forth laser scanning of the Ti6Al4V sample with length of 1 cm, laser power density of 19.1 kW/mm^2 and scanning speed of 1.2 m/s at the top surface reaches about 3000 K, rapidly decreases to 400 K, then increases up to 1450 K during second scan (Figure 4).

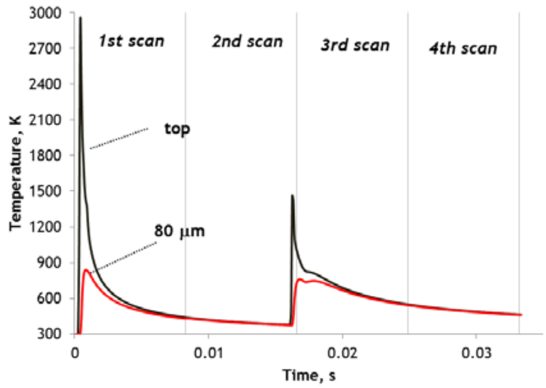
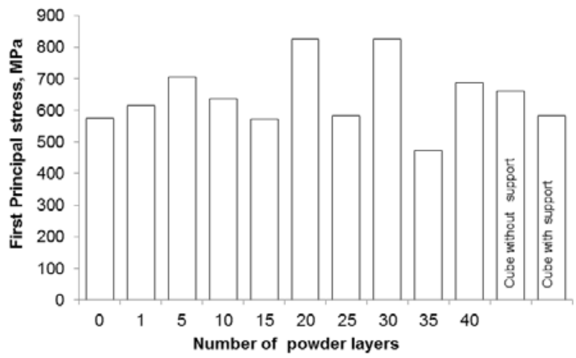


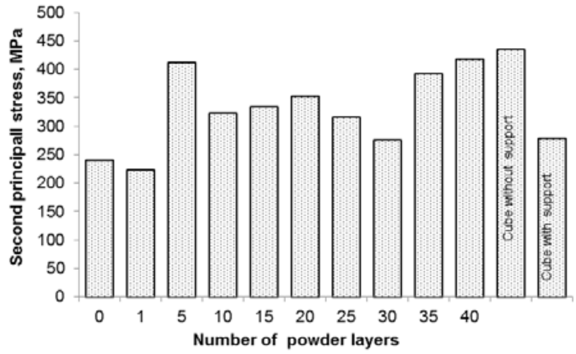
Figure 4 - Temperatures during back-and-forth laser scanning of the Ti6Al4V sample with length of 1 cm, the laser power density of 19.1 kW/mm^2 and the scanning speed of 1.2 m/s; the hatch distance is of 100 μm.

Various layers of material cool down at different rates, therefore contraction also occurs at different speeds. During laser melting, high compressive and tensile stresses are present under the front of the molten pool [Yadroitsava et al., 2015; Yadroitsev et al., 2015]. As a result, deformations in the surrounding material and the solidifying track occur.

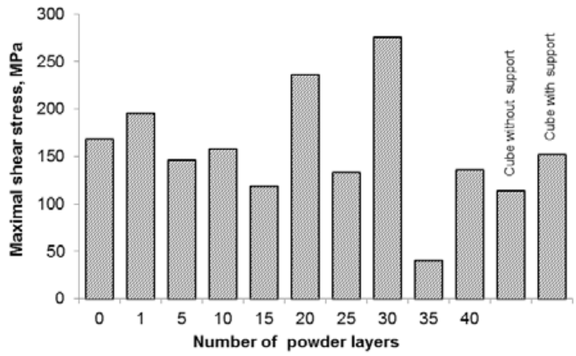
Residual stresses measured by XRD method in the middle point near the surface of as-built DMLS samples, are shown in Figure 5. Residual stresses were tensile and their values are significantly varied: from 800 MPa for major stress to 220 MPa for minor residual stress. No significant correlation was found between the number of powder layers, the surface roughness and value of the maximum principal residual stresses.



(a)



(b)



(c)

Figure 5 - Residual stresses on the top surface of the samples: maximal (a), minimal (b) and maximal shear stresses (c)

The direction of the maximal principal stress coincided with the direction of the laser scanning of each of the top layers. It was found, that the average maximum height of profile *Rz* correlated with second principal stress, which is perpendicular to the scanning direction. Coefficient of correlation was of – 0.8479 (Figure 6). Electrolytic removing of 15–80 µm was used to determine residual stresses of the samples consists of 1, 5, 25 and 40 layers. Results are shown in Figure 7. After electrolytic removal of top layers, measured principal residual stresses were 630–150 MPa, which is lower than those measured near the surface.

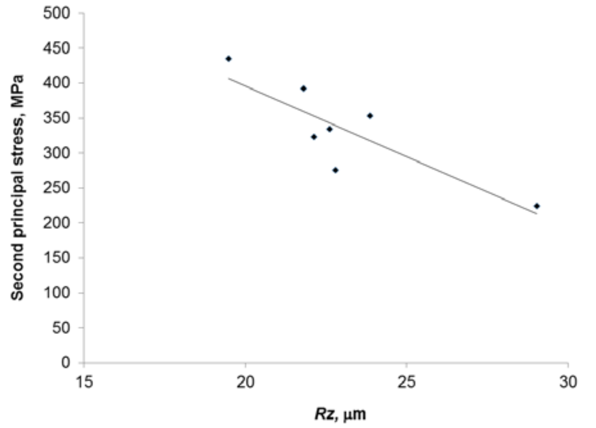
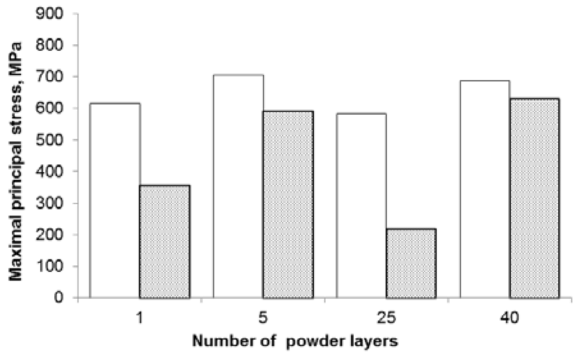
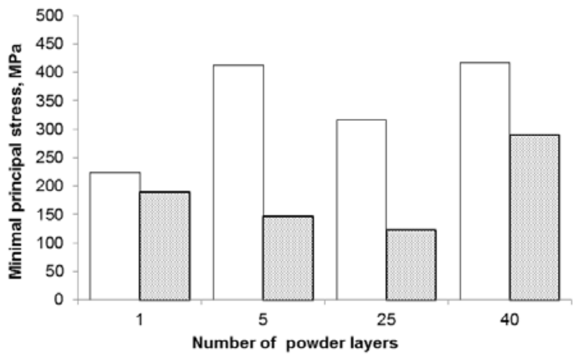


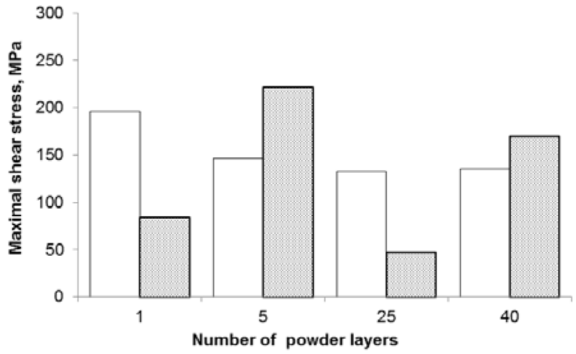
Figure 6 - Second principal stress *versus* Rz for powder layers.



(a)



(b)



(c)

Figure 7 - Residual stresses on the top surface (white) and in depth of 15-80 μm (grey colour)

The reason can be in-situ heat treatment happened during scanning of upper layers. As was calculated, due to thermal diffusivity at depth of 80 μm the temperature reaches about 840 K which is close to stress-relieving temperature 750-920 K (Figure 4). Also, M280 machine applied different process-parameters and scanning strategy for top and inner layers. Different energy input can lead to different residual stresses. As indicated Fitzpatrick et al. (2005), sources of uncertainty in residual stress measurements and the accuracy of calculations depends on elastic constants, non-linearity due to texture, stress gradients with depth and micro-stresses due to plastic deformation or grain interactions, etc. A surface roughness or interference of the sample geometry with the diffracted x-ray beam can result in systematic error in residual stress measurements [Prevéy, 1986].

Residual stresses near the surface of the cube produced without support were close to the values of 40-layers sample. Separation from the support structures during manufacturing of the cube indicates that during process, at some point, the limit value of ultimate tensile strength for Ti6Al4V alloy (1.17 GPa), was exceeded. This, in turn, indirectly indicates that measurements were correct.

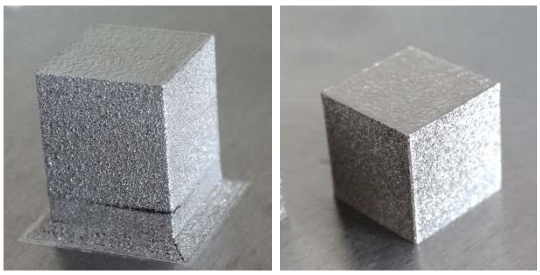


Figure 8 - Ti6Al4V cubes with/support

4 CONCLUSIONS

In the present work, experimentally measured residual stresses in DMLS specimens attached to the substrate were tensile and very high. XRD measured residual stresses had high variability, especially maximal shear stress. The direction of the maximal principal stress is coincided with the direction of the laser scanning. The average maximum height of the surface profile correlated with the second principal stress, which is perpendicular to the scanning direction.

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7 BIOGRAPHY

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Morakane Gloria Moletsane currently doing Master’s degree in Mechanical Engineering at Central University of Technology, Free State. The focus of her research is on microstructure and mechanical properties of Ti6Al4V alloy parts produced by DMLS.

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A Methodology to Evaluate the Influence of Part Geometry on Residual Stresses in Selective Laser Melting

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Abstract
The subject of residual stresses induced by the Selective Laser Melting (SLM) process has been one of the main focus areas in literature over the past decade. It has been reported that residual stresses can be responsible for shape and dimensional distortions, cracking and compromised mechanical properties (reduced yield and fatigue strength). These shortfalls limit the applicability of SLM components in industry, particularly for the aerospace industry where part lifetime and hence fatigue life is of utmost concern. High temperature gradients have been reported to be responsible for the residual stress build up. A key aspect that has not been considered in literature is part geometry and orientation and its influence on residual stress levels. Thus, this study proposes a methodology for investigating this influence for different geometric features. In this work, samples were built from tool steel powders. The Hole Drilling Method (HDM) and X-Ray Diffraction (XRD) techniques are proposed for measuring residual stresses. Preliminary results show that the geometry of a part influences residual stress magnitudes and distributions, with sharper ends exhibiting higher stresses than less sharp specimen ends.

Keywords
Selective Laser Melting, Residual stresses, Part geometry, Residual stress measurement

1 INTRODUCTION

One of the inherent phenomena of additive manufacturing, particularly Selective Laser Melting (SLM), is the build-up of residual stresses [1]. In order to achieve parts with high densities, high temperatures are required for the full melting of the powders - usually twice the melting temperature of the material [2]. The localised heating and melting of powders, coupled with the short interaction of the high energy laser beam with the powder bed, generates rapid heating and cooling cycles [3], [4]. This induces thermal gradients and consequently residual stresses in the part under consolidation [2], [5], [6], [7], [8]. Besides high thermal gradients, a host of other factors also contributes to the magnitude and distribution of residual stresses. These factors include thermal properties of the material, layer thickness, part thickness, scanning strategy and so on. In this work, we propose a methodology for evaluating the combined influence of building orientations and geometrical features such as fillets, chamfers and sharp edges on occurrence of residual stresses.

2 UNDERSTANDING RESIDUAL STRESSES

The phenomenon of residual stresses can be a significant problem in SLM and other processes based on similar technologies [9] such as Electron Beam Melting, Laser Engineered Net Shaping (LENS) [10] and Microwelding. SLM can be regarded as a series of micro-welds and therefore the same residual stresses encountered in micro-welding are also present in SLM [11]. According to Vrancken et al. [12], the SLM process results in the highest residual stresses among the metal additive manufacturing methods. These stresses have been reported to cause part distortion [8], pores, cracks and delaminations [2], [13], [14], [15], and even plastic deformation during consolidation [16]. Mercelis and Kruth [17] have described two mechanisms that are responsible for the formation of residual stresses in SLM. The first mechanism is attributed to the heating of the material when irradiated by the laser. Upon exposure, the material expands. This expansion is partially hindered by the underlying cooler solidified substrate, resulting in a compressive stress condition. These compressive stresses may be sufficiently high to induce plastic deformations [13]. The second mechanism occurs upon cooling of the material after exposure. The material shrinks upon removal of the laser beam. However the shrinkage is hindered by the plastic deformation that was developed during heating. Furthermore, the underlying solidified layer hinders the contraction of the top layer. These mechanisms result in a tensile residual stress in the upper surface [3], [13], [17]. Residual stresses are more pronounced in dense parts compared to porous parts as porosity tends to relax residual stresses

[3], [13] such that the stress normal to a pore is zero [3].

2.1 Influence of Part Geometry on Residual Stresses

Part geometry, particularly length and the second moment of area influence the occurrence and magnitudes of residual stresses in final parts [18], [19]. Previous experiments have shown that residual stresses tend to decrease through the part thickness [18]. This is attributed to underlying layers being exposed to a greater number of laser beam passes. A higher number of laser beam passes acts as a form of post treatment (or laser surface re-melting) which has the effect of reducing residual stresses [18].

2.2 Influence of building orientations

Building orientations have a reported impact on the mechanical strength of finished parts. From their work on SLM of stainless steel 316 L, Meier and Haberland [20] conclude that specimens built vertically show lower tensile strength and reduced ductility when compared to those built horizontally. Vrancken et al. [12] carried out a study on building orientations and stack building influence on mechanical properties, including residual stresses. They conclude that specimens built vertically have high fatigue crack growth rate. The influence of building orientations on toughness properties was investigated by Kruth et al. [21] and it was found that the building direction has negligible influence on toughness of samples although a significant influence of part geometry on toughness properties was recorded. Manfredi et al. [22] used four “orientations” to evaluate the properties (density, tensile strength etc.) achievable for Direct Metal Laser Sintering (DMLS) of AlSiMg. More orientations should be considered to include all the three building planes (XY, XZ and YZ); this is the objective of this work’s experimental plan. According to Meier and Haberland [20], the building orientation affects the tensile strength of parts, with horizontally built parts exhibiting higher strength compared to vertically built ones and even those manufactured using conventional means. These findings are also in line with conclusions by Vrancken et al. [12].

2.3 Influence of scanning vector length

Employing short scan vectors has been reported to reduce residual stress [3]. This is so because when the scanning area is small and short scan vectors are used, the laser beam scans successive lines in a very short space of time such that the temperature of the already scanned area will still be high when the laser beam scans along another path. This way, temperature gradients are reduced between neighbouring scan lines, resulting in reduced thermal stresses. On the other hand, long scan vectors promote cooling of the already scanned area because the laser beam should travel a long distance along the scanning area. In this case, the high temperature differences between scanned area and the new scan line results in greater thermal stresses [23]. The direction of scanning also determines the direction of thermal stresses. Jhabvala et al. [16] observed that residual stress-related bending was in the y-direction, orthogonal to the scanning direction chosen.

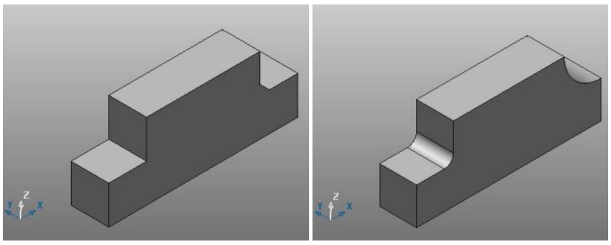
3 MATERIALS AND METHODS

3.1 SLM with m2 lasercusing system

The specimens were fabricated using the M2 Laser Cusing machine installed at Stellenbosch University’s Rapid Product Development Laboratory. The machine has a building envelope of 250 x 250 x 280 mm and is equipped with a 200 W continuous wave Yb:YAG solid state fibre laser. Laser focus diameter can be varied from 70 – 200 μm, and the powder layer thickness permissible is 20 – 50 μm. This machine uses the island exposure strategy, patented by Concept Laser GmbH, in which the scanning area is divided into 5 mm X 5 mm squares which are scanned randomly [3], [13], [24].

3.1.1 The geometries

Previous geometries that were considered in SLM were mainly to do with evaluating the achievable dimensional accuracy, minimum feature size, minimum wall thickness and manufacturability of overhangs [2], [25], [26]. In this work, components of the same length, width and height were built according to geometries given in Figure 1. The chosen geometries and associated features are in line with previous studies to evaluate influence of building orientations and features on strength properties of finished parts [12], [20], [22]. These geometries make it possible to investigate how the presence or absence of certain geometric features (such as chamfers, sharp edges and fillets) influences the magnitudes of residual stresses in SLM. The success of measurement of residual stresses is dependent on the size and shape of the component to be measured. In this study, the selected geometries make it possible to conveniently measure residual stresses using the Hole Drilling Method (HDM) and X-Ray Diffraction (XRD) technique. Geometry 1 is a block with sharp edges and a chamfer (Figure 1(1)). It is expected that the action of the laser beam cannot be the same for the two ends (sharp corner versus chamfered one) due to the difference in the scan lengths associated with each of these ends. This is the motivation for choice of geometrical features and applies to geometry 2 as well. Geometry 2 is a modification of geometry 1. This modification includes fillets in place of sharp and chamfered edges as shown in Figure 1(2). As with geometry 1, the presence of these features results in anticipated differences in heat transfer regimes for the different radius of fillet. Overally, geometry 1 and geometry 2 are expected to exhibit some difference in the residual stress magnitudes and distributions due to the differences in scan lengths and heat transfer dynamics around the features.

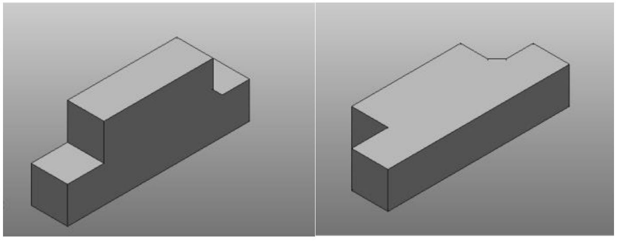


(1) (2)

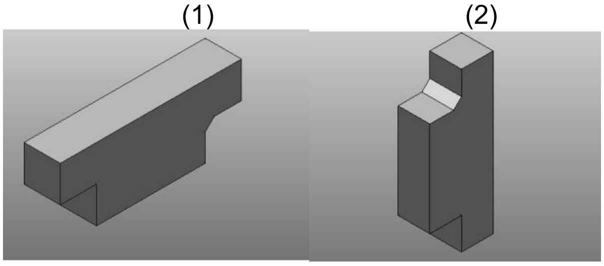
Figure 1 - CAD model for Geometry 1 and 2

3.1.2 Building orientations

Four building orientations or planes were chosen for the proposed specimen as given in Figure 2 and 3. The planes shown in Figure 2 and 3 are XY (specimen 1 & 5 i.e. +Z direction), XZ (specimen 2 & 6), XY (specimen 3 & 7 i.e. -Z direction) and ZY (specimen 4 & 8). As evident from these geometries



(1) (2)



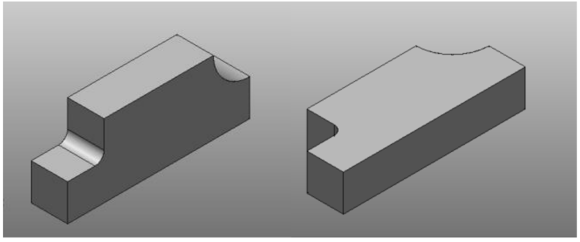
(3) (4)

Figure 2 - Building orientations for Geometry 1 with sample number/label

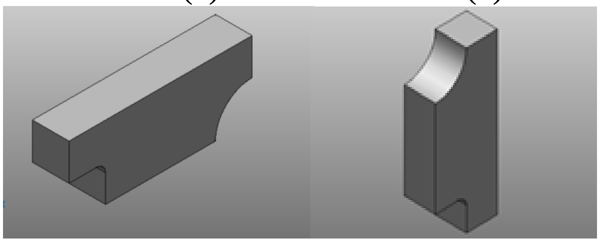
and orientations, specimens 3, 4, 7 and 8 will need supports in order to be built robustly. All the specimens were built from tool steel powder. The specimens were built on one base plate and, therefore, the same process parameters were employed for all the samples in their respective orientations. Wire Electron Discharge Machining (Wire EDM) was used to cut off the specimens from the baseplate and to remove supports.

3.2 Measurement of Residual Stresses

Two measurement methods – Hole Drilling strain gauge Method (HDM) and X-Ray Diffraction (XRD) technique - are proposed in order to check consistency of the results. HDM involves the drilling of a small hole in the material to be tested and using strain gauges to measure changes in strain state.



(5) (6)



(7) (8)

Figure 3 - Building orientations for Geometry 2 with sample number/label

When a hole is drilled in a material, the locked-up stress is relieved and a corresponding change in the strain state is recorded using strain gauges. The change in strain is then related to the stress state through a series of equations through the theory of Kirsch [15], [18]. XRD is the most widely used [19] non-destructive residual stresses measurement technique. Since material deformations cause changes in the spacing of the lattice planes from their stress-free value to a new value that corresponds to the magnitude of the applied stress [27], these changes can be used to evaluate internal strains and stresses in a material. This method is limited to shallow depths [28] or near surface regions [29]. Test surfaces should be thoroughly cleaned to remove grease, coatings and roughness, which may act as barriers to the X-ray beam, leading to many errors [19], [28]. In this work, the D8 Discover Diffractometer was employed for residual stress measurement.

For both methods, the measurements will be taken from the faces of the specimens as shown in Figure 4. Since the objective is to study the influence of the geometric features on the residual stress distributions, three reference points are chosen for the two specimens as shown in Figure 4 (represented by the small circles). The mid-point (2^{nd} point) will be used as the control point whereas the other two points near the geometric features to be studied will be the measurement points. The measurement points are located close to the features whose influence on residual stresses is to be evaluated at Cartesian coordinates (12, 10) and (38, 10), with the control point being situated at (25, 10).

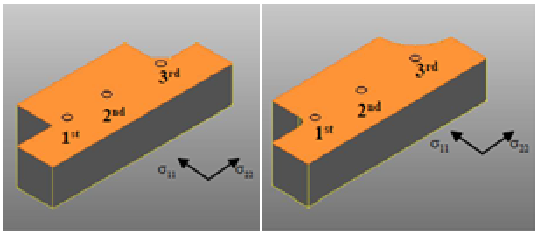


Figure 4 - The measurement positions

4 XRD MEASUREMENT RESULTS

Figures 5 and 6 show the results of the residual stress tensor components (σ_{11}, σ_{22} and σ_{12}) as functions of position along the length of the samples. The results show tensile normal stresses, σ_{11} and σ_{22} for specimen 2; relaxing laterally from ~200 to 124 MPa and ~540 to 453 MPa respectively. A similar trend is observed for σ_{22} on specimen 1, relaxing from 378 and 247 MPa. On the other hand, a change in stress from 130 MPa tensile to 10 MPa compressive is observed for the normal component σ_{11} of specimen 1. For both specimens, the residual stress magnitudes do not change significantly from point 2 to point 3. The shear stress components do not show significant variation. As expected, the sharper corner of specimen 1 (1st point) exhibits comparatively very high residual stress when measured against the control point (34 % higher for point 1 than point 2 for the σ_{22} component). On the contrary, reducing the sharpness of this corner on specimen 2 results in a much lower percentage residual stress difference (approximately 11 %) between point 1 and point 2 for the σ_{22} component. The same trend is observed for the σ_{11} component whereby anapproximate 120 % reduction of residual stress is realised for specimen 1 against a much lower 50 % reduction for specimen 2. Furthermore, for the σ_{11} component, the stresses at the sharper end (point 1) are 108 % higher than at the less sharp end (point 3) for specimen 1. A similar trend is observed for specimen 2, with point 1 exhibiting approximately 38 % higher stresses than point 3 (less sharp end). For the σ_{22} component, the same trend is observed that the sharp ends exhibit higher stress values (at approximately 34 % for specimen 1 and 16 % for specimen 2). Generally, the measured residual stresses are higher for specimen 2 than specimen 1, probably due to the different sample positions on the building platform.

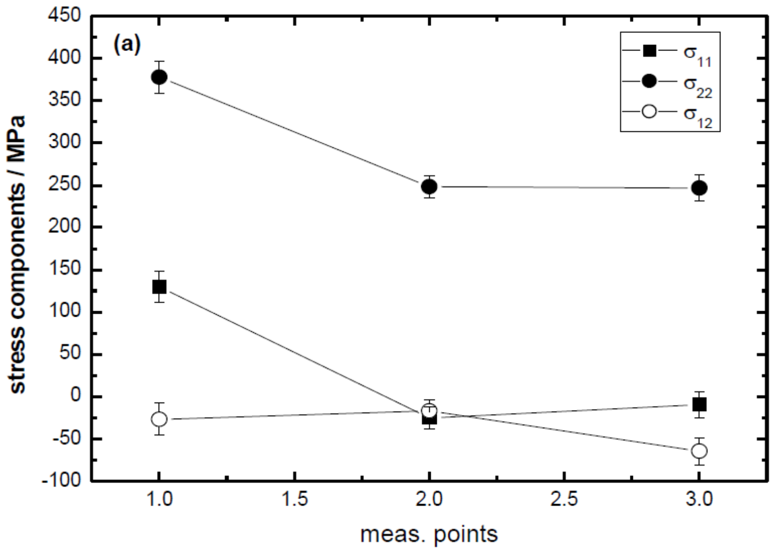


Figure 5 - Stress components for specimen 1

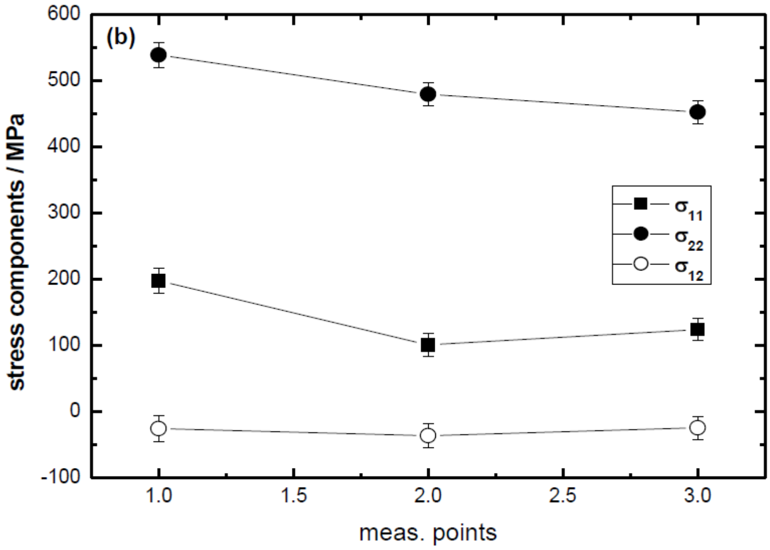


Figure 6 - Stress components for specimen 2

5 CONCLUSIONS AND FUTURE WORK

Preliminary experimental results point to the following important conclusions:

- High residual stresses which are largely tensile in nature were recorded for both specimens. The observed trend is that these residual stresses relax from position 1 to 3 for both specimens.
- The sharper edges of the specimens exhibit higher stresses and these stresses are relaxed as the sharpness is reduced.
- For both specimens, the σ_{22} stress component is greater than the σ_{11} component.This trend can be attributed to the greater distances between scanning sectors along the length of the specimen (corresponding to σ_{22}) than across its width. This in agreement with literature that residual stresses are higher for larger scanning sectors.
- The shear components of stress are small and do not vary significantly along the specimen length, especially when compared to the normal stress components.
- The control points exhibit different residual stress values, although these values follow a similar pattern. This is probably due to the different sample positions on the baseplate, whose influence on residual stresses should also be evaluated.

The observed differences in stress magnitudes for the two specimens sets a good basis for future investigations to involve studying the influence of sample position on residual stress distributions, further building on the work done in literature. The samples built in the XY (-Z direction) and YZ directions (i.e. samples 3, 4, 7 and 8) will have residual stresses relieved before actual measurement owing to wire EDM. This should have a direct effect on the magnitude and distribution of the residual stresses around the measurement locations. It is also evident that the total scanning area for sample 4 and 8 is much smaller (maximum 200 mm^2) compared to all the other samples (maximum 1000 mm^2), thanks to the chosen orientations. This means that the time to scan neighbouring islands is shortened, resulting in reduced temperature gradients between islands. However, the Least Heat Influence (LHI) [23] which is expected to reduce thermal stresses becomes inapplicable. Against this background, it will be interesting to evaluate the influence of the scanning area on residual stresses.

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7 BIOGRAPHY

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Characteristics of Single Layer Selective Laser Melted Tool Grade Cemented Tungsten Carbide

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Abstract

Cemented carbide tools, specifically tungsten carbide based alloys, have found a wide range of application fields including manufacturing, agriculture, and mining, among others. A need for customised tooling solutions using cemented carbide alloys have been identified. Additive manufacturing is chosen as a novel manufacturing process due to its superior material and process flexibility. The study investigates the melting behaviour observable during the SLM process using a tool grade cemented tungsten carbide powder. The laser power, scan velocity, and hatch spacing of the SLM process are varied and single powder layers are sintered accordingly. This is done to determine the varying influence these parameter combinations have on the melting behaviour of the material during sintering. For each set of parameter combinations the test samples were analysed using microscopic imaging. It is found that a combination of high laser power, high hatch spacing, and low scan speed yields the best results.

Keywords

Additive manufacturing, carbides, process windows

1 INTRODUCTION

The South African (SA) manufacturing industry faces specific challenges such as a relatively limited market - as compared to the European and US industries – as well as competition from Eastern sources (e.g. China's tooling industry) using low manufacturing input costs. In the SA context a rising need for customised industrial application solutions exists. Using customised tools could provide a competitive advantage allowing SA to compete on a global scale. Areas of customisation include tool geometry and material composition. Materials include carbon and alloy steels, stainless steels, cast iron, aluminium and titanium alloys, polymers, ceramics, tungsten carbide alloys, cermets, and other composites. Tools used in a wide range of industrial applications rely on the superior wear resistance and hardness of hardmetals, such as cemented carbides [1]. Cemented carbides consist of a carbide phase that provides excellent wear resistance and a binder phase that provides toughness and ductility. For specialist applications of cemented carbides, SA players need to exploit market niches where local conditions define a unique product. For example, Allen and Ball [2] determined that wear rates can vary by up to 20 orders of magnitude in agricultural applications. In power generation, ceramics and cemented carbides offer the ideal abrasive wear resistance required. These applications all require specific tooling solutions. SA players must be provided with rapid prototyping (RP) capability, using cemented carbide materials, to open up new possibilities. Specifically purposed tool design, as well as the ability to iteratively adapt the tool, is required. In additive manufacturing (AM) processes several variables influence the final part properties. In powder-based AM, these include the material, the process, and the energy source used to sinter the material [3]. Process related parameters include single layer thickness, scan velocity, hatch spacing, and scan strategy. An example scan strategy is the island scan strategy patented by Concept Laser GmbH that divides the scanned area into square sections (or islands) [4]. The scan sequence is randomised to determine in what order each island is scanned. Laser specific parameters include laser power, spot diameter, wavelength, and energy per laser pulse. Material specific parameters include type, particle size, particle distribution, particle shape, and percentage composition. To improve upon the resultant part properties using selective laser melting (SLM) and hardmetal powders, the laser power, scan speed, scan interval, powder mixture ratio, and particle shape and size influences must to be investigated [5]. To achieve favourable microstructural and mechanical properties, significant emphasis is required on the design strategy of powder materials as well as the laser control processes [6]. Thus a specifically tailored production strategy must be designed for a novel material. Investigation of single layer formation in a SLM process could establish a foundation for defining processing parameters for the powder material under investigation [7]. Kruth et al. [8] identified two crucial parameters influencing the dimensional control of the scan tracks: 1) scan speed and 2) laser power. Scan speed relates to track width, whereas laser power affects track thickness. Other parameters, found to also influence the formation of single layers, include layer thickness and hatch spacing, among others. Varying combinations of these parameters enables the formation of process windows, based on the observable melting activity. Process windows must be established experimentally for any novel material to avoid scan track instabilities (such as spheroidisation) and excessive part porosity [9]. Spheroidisation is the formation of isolated metal spheres having a diameter equal to the incident laser beam [3], [6], [10], [11]. The material is rapidly melted, and subsequently cooled, due to the rapid scan speed. Successful wetting of the underlying layer is hindered and the tendency to reduce the surface free energy dominates the molten material behaviour, thus forming these spheres. Gu and Shen [11] termed this 'shrinkage-induced balling' which they attributed to a significant capillary instability effect. The formation of these spheres hinders subsequent powder deposition and results in a decrease of the layer and final part density, as well as a reduction in the mechanical properties [3], [10], [11]. Several single layer experiments using an unconventional powder produced process windows identifying four melting states: 1) over melting, 2) moderate melting, 3) spheroidisation, and 4) insufficient melting [7], [12], [13]. The process windows are established through varying combinations of scan speed and laser power. Careful selection of both laser processing and powder deposition parameters are necessary to establish a suitable processing window and avoid spheroidisation [6]. This is required to maintain a moderate temperature field and avoid overheating of the powder material. A parameter relating laser power (*P*), scan speed (*v*), hatch spacing (*h*), and layer thickness (*d*) is the volumetric energy density (VED):

$$VED = \frac{P}{vhd} \tag{1}$$

High VED [$J.mm^{-3}$] values are required to initialise melting activity in the powder bed. This should be limited to slightly higher than the material's melting temperature. Lower hatch spacing increases the VED in the powder bed. Increasing the temperature beyond the melt point of the material results in evaporation of the powder [1], [2]. Rapid expansion of the evaporating particles creates an overpressure in the melted zone, resulting in material ejection from the powder bed. This occurrence leads to the formation of surface protrusions in single layer samples and could become prevalent where complete melting of the cemented carbide is desired.

The choice in energy source in laser melting is an important factor influencing the consolidation of powders. This relates to 1) the energy absorptivity of materials being dependent on the laser wavelength and 2) powder densification being dependent on the incident laser energy on the powder bed [6]. Furthermore, the laser contact time determines the amount of laser energy transmitted to the powder bed. Contact time in SLM is usually between 0.5 and 25ms. This is dependent on the spot diameter and the scan speed. Fully molten powder particles cannot be achieved unless high laser power levels are used, due to the short exposure time. A particular difficulty associated with SLM is scan track formation and the subsequent shrinkage behaviour observable. Individualised scan tracks promote uniform single layer formation. Part stability, the corresponding increased part density, and the associated mechanical properties are dependent on uniform single layers. Hatch spacing, scan speed, and laser power have been found to be the dominant factors affecting how well an individual scan track is formed [6], [14]–[17]. Specfically, hatch spacing relates to the amount of scan track overlap and determines the amount of energy dissipated into the substrate, previous scan tracks, and the raw powder [18], [19]. The incident energy reheats the previous layer and the substrate and conducts heat to the unmelted powder. The second scanned track appears lower than the first and the powder consolidation zone diminishes. The occurrence of this phenomenon relates to shrinkage phenomena. Shrinkage commonly occurs in conventional and novel sintering of cemented carbides [20]. Parts experience varying degrees of shrinkage, dependent on the nature and properties of the material used [1]. During SLM the material experiences thermal expansion upon heating of the powder bed. As the melted tracks cool and solidify, the particles rearrange and shrinkage occurs. The use of finer powder particles leads to faster onset of shrinkage. Catastrophic process failure by delamination was extensively studied by Yasa et al. [21] and noted to be a function of both shrinkage and the occurrence of elevated edges. The formation of elevated edges is explained as a consequence of surface tension. A scan track will assume a form minimising surface tension and maximising volume (i.e. a round cross section in a cylindrical shape). The first scan line is surrounded by unmelted powder with low thermal conductivity. As the melt pool changes, powder particles are drawn towards the melt volume, increasing the melt pool, and altering the solidification rate. This results in lower amounts of powder available for subsequent scan tracks. The result is lower adjacent scan tracks. Spheroidisation, and other defects, also result from the presence of oxide layers between powder particles and previously processed layers. Reduction of surface oxides is required to enable direct metal to metal interfaces [6]. This will encourage successful wetting in the SLM powder system. Oxidation is reduced or avoided by conducting AM processes in inert environments, such as argon gas. Even under extremely low partial pressure of oxygen, most metals form oxides at their respective melt temperatures. Li et al. [7] analysed W-Cu samples produced by SLM that showed lower part densities than for conventional PM. This is attributable to non-melting of the hard phase and limited liquid phase content under the investigated processing parameters. Part densities may be increased by a decrease in scan speed, using narrower hatch spacings, and material exposure at higher laser power [7], [13]. SLM is capable of producing high part densities; however the process develops residual stresses in the material, derived from the high thermal gradients induced in the material. Part distortion, cracking, and/or delamination are but a few defects that could result from excessive residual stresses [3], [6]. Many authors specifically focus on the effects of changing laser power, scan speed, and layer thickness in a SLS/SLM process and how it influences the achievable single track, single layer, and multi-layer sample properties [15], [16]. Others investigate different hatch spacing values and the associated effects on each of these different production phases [18], [19]. Similarly, several works are presented on SLS/SLM using different materials and what the effect is of different material characteristics on achievable properties in single scan tracks and layers, as well as multi-layered samples. Finally, authors have also focused on determining the specific formation mechanisms associated with, for example, residual stress and balling [17]. From this it is clear that the production of cemented carbide parts using SLM technology is feasible and of great interest. The melt behaviour and associated defect formation during processing, however, remains a topic that requires further research. This work investigates single layer formation of a tool grade cemented tungsten carbide material in a SLM system. The influence that varying levels of laser power, scan speed, and hatch spacing have on the single layer formation is the primary focus of this work.

2 EXPERIEMENTAL METHODOLOGY

2.1 Single layer sample production

The 16 test samples for this study are produced from WC-6.6wt.%Co with a M2 LaserCusing® SLM machine from Concept Laser GmbH according to the experimental design outlined in Table 1. The samples are 35x35mm squares. The geometry is used for simplicity and ease of analysis. Magics® software is used to prepare the Computer Aided Design (CAD) model and produce the 2D slice model data. The slice data are exported to the SLM machine which is then used to scan each layer, building the final 3D part. In this work only a single layer is scanned for each parameter set. A uniform powder layer is sieved onto the baseplate to a thickness of 150µm. The machine is sealed and the build chamber flooded with argon gas, thereby creating an inert environment. At oxygen levels below 0.9% the scanning process may commence. The machine is capable of processing multiple build parameters for multiple parts at once. As such, all 16 samples are created on the same build platform during a single experimental run.

2.2 Microscope anlaysis

The single layer test samples are analysed using an Olympus SZX7 Stereo-microscope System. The software used is Olympus Stream Essentials. Microscope images are captured at 1.25 and 3.20 times magnification. The observable differences in single layer formation, as a result of different production parameter sets, are studied by graphing the samples according to high-low, low-high, low-low, and high-high combinations of power and scan speed. This is done for each hatch spacing value which is either 0.075mm, 0.100mm, 0.125mm, and 0.150mm.

3 RESULTS AND DISCUSSION

3.1 Microscope analysis

The microscope analysis is broken down into four primary focus points: 1) protrusion formation on the sample surface, 2) shrinkage activity present (i.e. valley formation), 3) scan track formation, and 4) balling present in the scan tracks.

3.1.1 Protrusion formation

All 16 samples exhibit protrusion formation on the surface. The extent of the formation depends on the combination of laser power, scan speed, and hatch spacing. This can be explained by the near-excessive VED levels developed in the powder bed during processing. In this work, as the layer thickness is held constant and the laser power and scan speed have only two levels (high and low), hatch spacing is the primary factor explaining the differences in the observable phenomena for each sample. Samples produced having a high VED (corresponding to a low hatch spacing) experience increased material ejection on the sample surface during processing. SLM is characterised by rapid melting and subsequent solidification of the material. The ejected material is thus trapped on the surface of the sample by the solidifying material. An increase in hatch spacing decreases VED which corresponds to a reduction in protrusion formation. This is shown in Figure 1 which shows all 16 samples produced. The protrusions appear as dark spots on each sample surface.

3.1.2 Shrinkage

The single layer samples in this work exhibit localised shrinkage near the island edges as well as the sample contours. This is explained by the rescanning of the island edge when an adjacent island is scanned. The rescanned area undergoes a second cycle of thermal expansion, particle rearrangement, and subsequent shrinkage. The process continues as the scan tracks are re-melted and reaches a plateau once particle rearrangement is no longer necessary or possible. It should be noted that shrinkage does not appear uniformly across any of the sample surfaces. The width, length, amount of shrinkage, and placement varies with the associated process parameter values. In some samples, the observable shrinkage increases as scan speed and hatch spacing increases. The occurrence of shrinkage at localised regions has the undesired effect of encouraging porosity formation.

Uniform deposition of powdered material will create thicker layers in areas where shrinkage is pronounced. The incident laser energy doesn't penetrate the material far enough to fuse to the previously sintered layer, resulting in unmelted powder being trapped beneath the newly melted layer. Unmelted powder has a

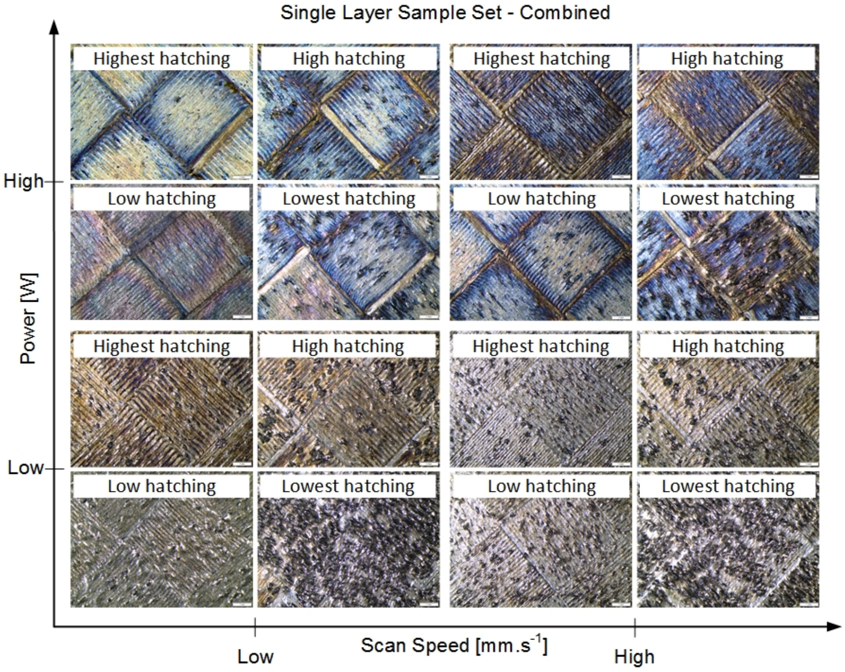

Figure 1 - Combined microscope images of single layer sample parameter sets, according to hatch spacing.

EXPERIMENT NAME	SCAN SPEED, v [mm/s]	LASER POWER, P [J/s]	HATCH SPACING, h [mm]	LAYER THICKNESS, d [mm]
E1	100	100	0,1	0,15
E2	200	100	0,1	0,15
E3	100	200	0,1	0,15
E4	200	200	0,1	0,15
E5	100	100	0,15	0,15
E6	200	100	0,15	0,15
E7	100	200	0,15	0,15
E8	200	200	0,15	0,15
E9	100	150	0,125	0,15
E10	150	100	0,125	0,15
E11	150	150	0,125	0,15
E12	100	100	0,125	0,15
E13	125	125	0,075	0,15
E14	175	175	0,075	0,15
E15	175	125	0,075	0,15
E16	125	175	0,075	0,15

Table 1 – Experimental design parameters and value combinations.

markedly lower density as opposed to the bulk material, which alters the mechanical properties of the built part. Furthermore, as unmelted powder is trapped between melted layers, unstable bonds are formed between these layers and delamination has a
higher probability of occurring. The single layer samples produced in this work exhibit localised tendencies to form elevated edges at both island and part contours.

3.1.3 Scan track formation

In this work it is observed that an increase in hatch spacing results in well-defined scan tracks. This follows since an increase in hatch spacing reduces the percentage overlap between adjacent scan tracks. Furthermore, it reduces the heat sink effect observable in single layer formation during SLM. Based on the experimental results observed here single layers with higher hatch spacing values yield favourable results. Samples with low hatch spacing exhibit obvious defects including pitting as a function of particle evaporation at low hatch spacing, balling as a result of low hatch spacing and moderate to high scan speed, and cracking as a result of low hatch spacing and high power.

3.1.4 Balling

Balling is visible in every sample, with the sample corresponding to P = 200W, v = 100mm.s^{-1}, and h = 0.150mm showing the least amount of balling. Balling is more prominent at high scan speed for both low and high laser power, corresponding to the definition of 'shrinkage-induced balling'. This shows that lower scan speeds yield more favourable results. It can also be seen that low hatch spacing yields higher levels of balling in the sintered samples. The binder material melts incongruently over a range of temperatures, exhibiting a larger degree of melt activity as the temperature increases above the solidus point. Excessive liquid formation is accompanied by a prolonged liquid lifetime (resulting from a higher energy input into the powder material), leading to considerably lower melt viscosity. A higher degree of superheat of the low melting phase results, enhancing the Marangoni effect. This forms a large amount of individual spheres with the associated diminishing surface energy. At lower hatch spacing values, the amount of thermal energy in the sample layer will be higher due to a larger concentration of laser energy per unit area, thus leading to the formation of individual balls. This suggests that high values for hatch spacing yield more favourable results. Combinations of high laser power resulted in less balling in the test samples produced in this work. Coupled with high hatch spacing, significantly better scan tracks showing less balling or defect formation is achievable. Parameter combinations with low laser power show a higher concentration of balling and/or protrusion formation. This suggests that parameter combinations of low scan speed, high hatch spacing, and high laser power will result in favourable single layer formation.

3.2 Process windows

The results in the previous sections are used to create process windows describing the expected observable single layer formation phenomena when selectively melting WC-6.6wt.% Co powder. Here, the process windows incorporate the effect of various hatch spacing values on the formation of single layers, shown in Figure 1. It is clear that a high laser power, low scan speed, and high hatch spacing combination leads to the best results. The resultant samples are characterised by low levels of protrusion formation, little to no balling, limited micro-cracking, and almost no shrinkage. This processing region is defined as the baseline parameter set to describe the observable phenomena in the remaining three regions. In comparison to the baseline, low-low (*P-v*) combinations for the remaining hatch spacing values are characterised by prominent protrusion formation and other surface defects. These defects include indistinguishable scan track formation, pitting, localised shrinkage, and a certain degree of balling. A similar observation can be made for low-high and high-high combinations of laser power and scan speed. When compared to the baseline process region, again it is clear that single layer formation is not as successful and surface defects are more pronounced. It is concluded that, for each combination (low-low, low-high, high-low, and high-high), as hatch spacing increases, the presence of surface defects decrease.

4 CONCLUSIONS

The following conclusions can be made from the results presented here:

1. Single layer samples were successfully produced using a SLM technology and tool grade cemented tungsten carbide powder.
2. Process windows were established to describe the expected melt activity observable for a given combination of laser power, scan speed, and hatch spacing.
3. Varying laser power, scan speed, and hatch spacing has a significant effect on single layer formation and results in different levels of surface defect formation.
4. The optimal processing region to produce single layers from a tool grade cemented tungsten carbide material corresponds to high laser power (*200W*), low scan speed (*100mm.s^{-1}*), and high hatch spacing (*0.15mm*). This corresponds to a *VED = 88.889 J.mm^{-3}*.

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STREAM B

Production Technologies and Systems

Session B1: Advanced Concepts in Forming

Session B2: The World of Composites

Session B3: Machining of Advanced Materials

Session B4: Advances in Metrology and Inspection

Session B5: Intelligent Manufacturing Concepts I

Session B6: Intelligent Production Systems

Session B7: Intelligent Manufacturing Concepts II

Hollow Shaft Concepts in Powertrain – Potentials for Efficiency Increase in Car Operation and Car Manufacturing

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Abstract
Sustainable action begins with sustainable production. In this context, the driving forces for progress and innovations in production engineering are complemented by another topic: resource efficiency. Examples for strategies and solutions leading to more efficient utilization of resources are the application of efficient technologies or the optimization of process chains by integrating and combining processes. However, using these strategies, not only product manufacturing can be optimized as regards resource utilization. Furthermore, the opportunity arises for saving resources during product operation, i.e. during vehicle operation. Thus the consistent application of strategies of lightweight construction in car body manufacturing leads to a reduction of fuel consumption and finally to a decrease in CO_2 emissions. One approach which is gaining more and more importance in the sector of vehicle manufacturing is substituting conventional solid shafts by hollow shafts. Considering the potentials of implementing concepts of hollow shafts in the production and the operation of vehicles for improving resource efficiency, the Fraunhofer Institute for Machine Tools and Forming Technology conducts research activities in this area which plays a major strategic role. Research on this topic is carried out in funded as well as in industrial projects. Hollow or constructed camshafts, crankshaft and gear shafts are main products realized within the framework of these projects. In addition to lightweight construction, the implementation of net-shape technologies represents a further objective to minimize resources for realizing these powertrain components. The contribution will present selected research activities of the Fraunhofer Institute for Machine Tools and Forming Technologies in this field. Furthermore, it will illustrate achievable effects concerning the weight reduction and efficiency increase in car operation as well as in vehicle manufacturing.

Keywords
Lightweight design, hollow shaft concepts, forming technologies

1 MOTIVATION FOR HOLLOW SHAFT CONCEPTS IN POWERTRAIN APPLICATIONS

Due to the current requirements to significantly reduce CO_2 emissions, the reduction of fuel consumption represents a main challenge for today's car manufacturing industry. Because of the close correlation between vehicle weight and fuel consumption, there is huge potential for meeting this challenge by employing measures to improve performance capability and increase the effectiveness of engines, but above all by reducing the weight of components.

Systematic use of lightweight construction, one of the most promising measures, plays a prominent role. The term lightweight construction has become a byword for revolutionary industrial development.

One approach which is gaining more and more importance in the sector of powertrain manufacturing is substituting conventional solid shafts by hollow shafts [1, 2]. The realization of such components offers a significant weight saving potential. Compared to solid shafts, weight savings of up to approx. 60% can be reached in camshafts, e.g. based on the application of forming technologies using active media or process combinations. Moreover, effects were verified regarding a significant reduction of production cost.

2 REALIZATION OF HOLLOW SHAFT CONCEPTS USING FORMING TECHNOLOGIES

Net-shape technologies or forming technologies are approaches for resource-efficient manufacturing of powertrain components for vehicles. Based on these approaches and combined with innovative part design it is possible to considerably reduce the material input compared to manufacturing concepts of solid shafts. This also implies significantly less mechanical processing. Furthermore, the component properties are positively influenced due to cold hardening of the material in the forming process.

2.1 Selected Examples

2.1.1 Lightweight camshaft

In combustion engines camshafts are parts essential for functioning under high dynamic loads. Thus many generations of vehicles were equipped with cast or forged camshafts. In addition to the disadvantage of high weight, this method also required a considerable amount of cutting when processing the cast or pre-formed shaft to the final product.

Considering the increasing importance of lightweight construction of vehicles, the camshaft was also investigated in terms of potential weight savings. Using hollow shafts offers substantial savings potential, yet hole drilling of a shaft would not be a very effective manufacturing technology. For this reason constructed camshafts were utilized on the basis of tubes. Lobes were manufactured separately and joined together with the tube by appropriate technologies.

The tube based camshaft technology was further developed by applying hydroforming, which also offers potential of optimization by extending the initial diameters while simultaneously reducing the thickness of the tube wall. Figure 1 shows a segment of a prototype shaft.

Figure 1 - Prototype shaft with relatively thick lobes.

The lobes can be manufactured thinner and thinner based on a specific near-net-shape forming of the camshaft tubes. Finally, real series shafts were realized by hydroforming (see Figure 2).

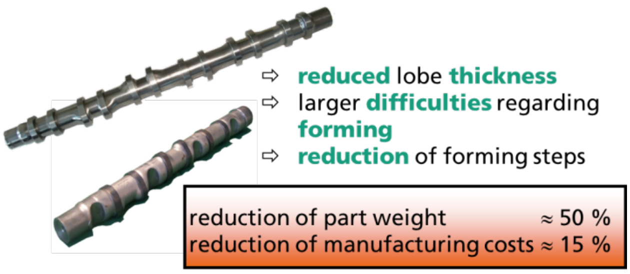

Figure 2 - Series shafts and efficiency effects.

When treating the surface with appropriate wear protection, the lobes can even be omitted. Consequently, two strategies have been developed for lightweight camshafts, as shown in Figure 3 [2].

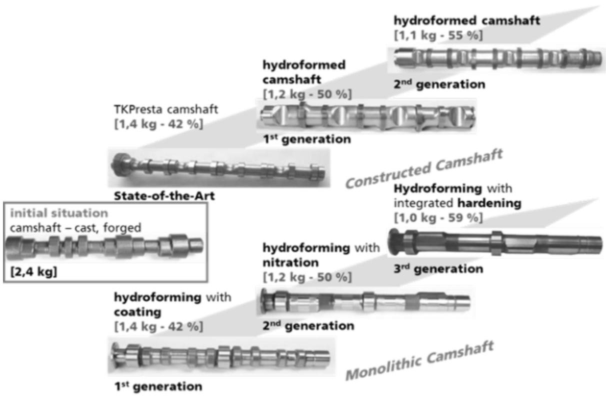

Figure 3 - Evolution of the lightweight camshaft.

The first tier represents the constructed camshaft consisting of a carrier tube and essential joined functional elements such as lobes and bearing rings. The second tier shows the monolithic camshaft which is also based on a tube. In constructed camshafts wear resistance is achieved by using hardened lobes. In monolithic lightweight camshafts, however, this wear resistance is realized by subsequent surface treatment, e.g. thermal spraying of a hard material coating or nitrating of the corresponding areas. One exception is the press hardened camshaft, representing the final evolutionary step of monolithic camshafts. This variant comprises forming at temperatures of approx. 850 °C. At the end of the forming process, the part is cooled down at a high speed while still in the tool, allowing for hardening. Thus, this variant is especially efficient regarding energy and resources since it combines forming and heat treatment. Moreover, it does not require separate joining of cam rings.

2.1.2 Gear shaft

Manufacturing of hollow structures is also suitable for gear shafts in order to reduce the weight of the parts. Furthermore it can be assumed that this method will also lead to more efficient part manufacturing when combined with innovative technologies and systems of manufacturing. In addition to reducing part weight, other desired effects include a decrease in material input or a reduction of manufacturing time. In gear shafts or drive shafts the component load causes maximum shear stresses in the cross-section close to the surface, and the load occurring in the core of the component is negligible. For these reasons, manufacturing of hollow gear shafts is feasible.

Forming technologies are suitable for manufacturing hollow gear shafts in order to optimize resource usage, including energy, material and time [2]. They can be applied, e.g. for realizing the hollow shaft, for preforming or forming of intermediate geometries and for realization of gears (see Figure 4).

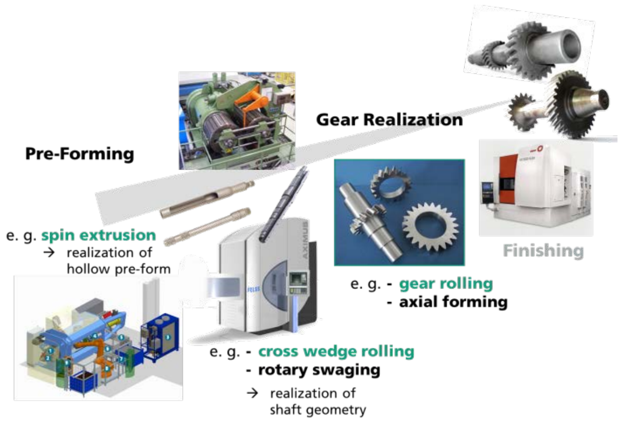

Figure 4 - Forming-based process chain for gear shaft realization.

The following chapters will present and discuss examples of forming technologies with an application potential of resource-efficient manufacturing of hollow gear shafts.

2.2.1 Manufacturing of hollow shaft using spin extrusion

In order to implement hollow shaft concepts it is important to realize the hollow shaft. This aspect needs to be evaluated regarding the total process chain and also concerning the economic efficiency. The state-of-the-art is characterized by using solid materials for the initial semi-finished product. Then the hollow shaft can be produced, e.g. by deep hole drilling. However, this method is not very material efficient.

Alternatively, hollow shafts can be manufactured from solid material by using forming processes, e.g. the so-called spin extrusion. This process was developed by the Fraunhofer Institute for Machine Tools and Forming Technology (IWU). It can be used for manufacturing axisymmetric hollow shapes from solid semi-finished products. Spin extrusion is an incremental forming process. The hollow structure is realized by the simultaneous operation of spinning rollers and a forming mandrel that produces the inner part geometry. This process can be performed at ambient temperature and with thermal assistance, depending on the required effective strains and the material used. Figure 5 demonstrates the principle of the process.

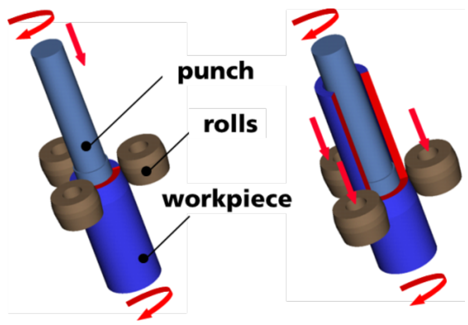

Figure 5 - Principle of spin extrusion.

Within the framework of funded as well as industrial projects one essential objective has been to verify the general feasibility and the possibility of series production. Furthermore the limits of application were determined. Figure 6 presents the process window of spin extrusion as an alternative to deep hole drilling and impact extrusion.

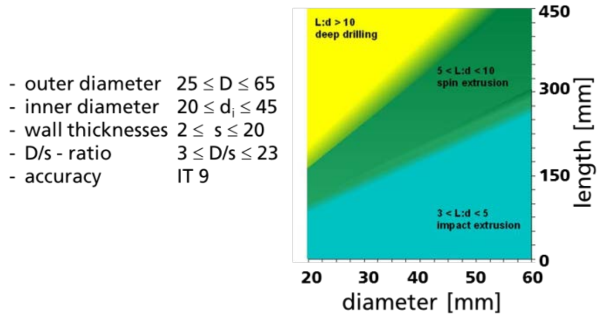

Figure 6 - Forming window of spin extrusion.

Compared to manufacturing of the hollow shaft by cutting, spin extrusion offers the decisive advantage of significantly higher material exploitation. Investigations of specific part examples demonstrated material exploitation of up to 90%, as shown in Figure 7.

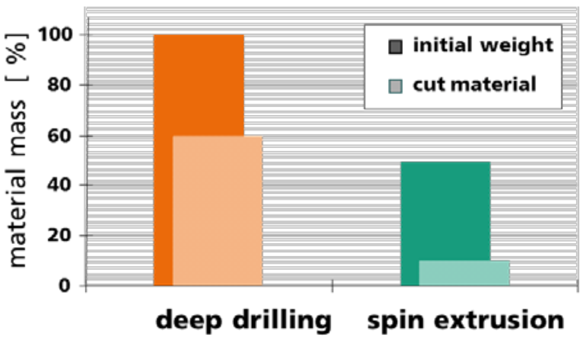

Figure 7 - Saving potential by spin extrusion.

2.2.2 Preforming by cross wedge rolling

Cross wedge rolling is another net-shape technology suitable for the realization of hollow gear shafts. This method can be used to manufacture preforms. The process is characterized by forming of initial semi-finished products with circular cross-sections using wedge shaped tools. The radial penetration of the wedges into the initial shape and the replacement of the material in axial direction cause a reduction of the initial diameter according to the geometry of the tools. Thus it is possible to realize optimized material distributions or preforms adapted to the final part geometry (see Figure 8).

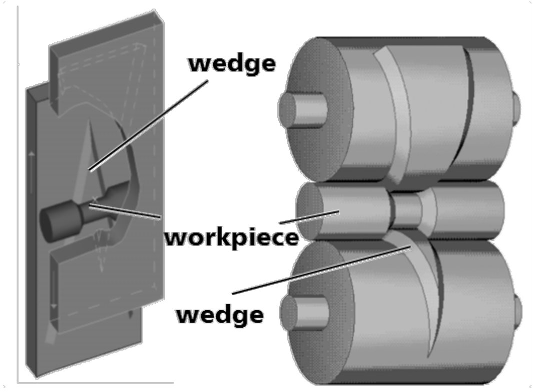

Figure 8 - Principle of cross wedge rolling with round and flat tools.

The application of cross wedge rolling as part of the process chain for gear shafts represents a significant research focus of Fraunhofer IWU in the field of bulk metal forming [3]. Within the framework of numerous research projects feasibility studies were also carried out on hollow gear shafts for automotive powertrains. Using prototypes basic feasibility was demonstrated in these projects. Furthermore corresponding analyses were conducted on the economic efficiency. Figure 9 depicts the modified process principle for realizing hollow preforms for gear shafts.

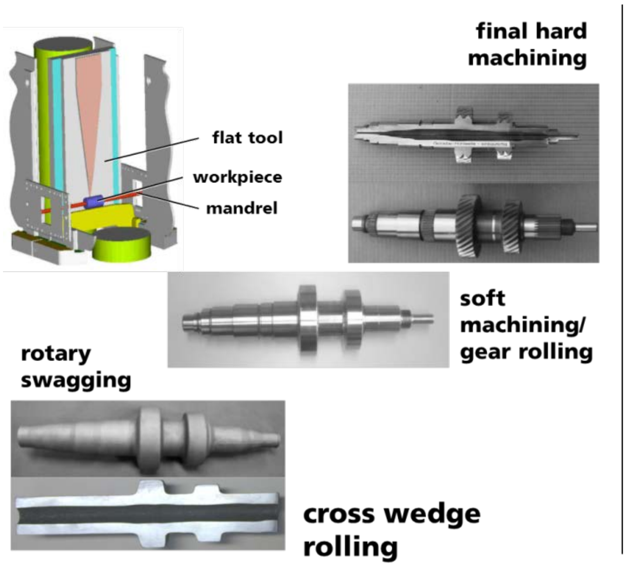

Figure 9 - Realization of hollow shafts based on cross wedge rolling

Considering the achieved results, the technology of cross rolling can be applied for optimizing the material use and also for manufacturing lightweight shafts. Thus expected effects also include reduction of fuel consumption and CO_2 emissions.

2.2.3 Gear realization by forming

Within the framework of the total process chain of 'geared hollow shafts' another important research focus lies on manufacturing of gear geometries by applying suitable forming processes. In particular, profile rolling is investigated as a process variant of cross rolling.

At Fraunhofer IWU the research focus regarding profile rolling lies on plunge cut processes using round rolling tools [4]. Particularly, investigations are carried out on applying this process to manufacture high gears. Figure 10 gives an overview of the progress achieved in the last years [5-8].

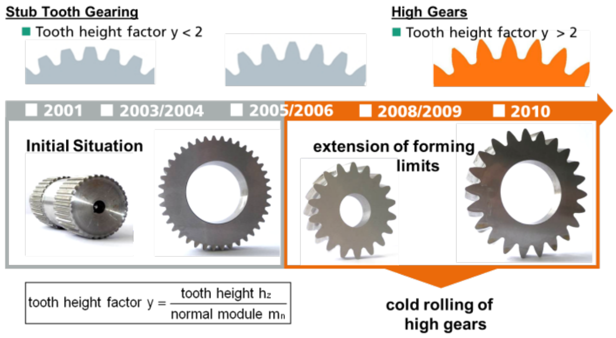

Figure 10 - Achieved progress in gear rolling.

Until recently, it has not been possible to realize high gears by forming technology, i.e. by rolling of high gears with large factors of tooth height (y > 2). However, the limits of this application were significantly extended in numerous research projects. Thus, the prerequisite was created for extending the field of application for gears.

Figure 11 illustrates the process cycle for the realization of gears by gear rolling.

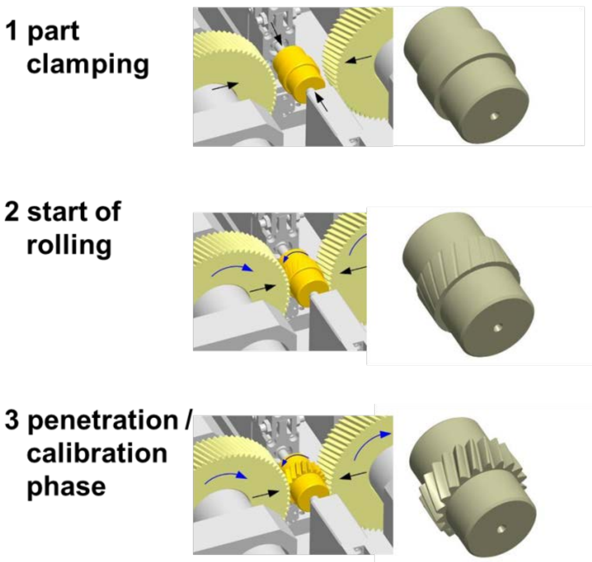

Figure 11 - Process cycle of gear rolling.

Based on this forming process, it is possible to substitute process steps that require high energy and cost, e.g. shaving and shot peening. Furthermore, considerable effects can be achieved concerning the manufacturing process for gears. Using real parts as examples, it could be demonstrated that it was possible to shorten the process time by up to 50% as well as to reduce the mass of material input by up to 30%, compared to processing by cutting. In this context the achievable effects are particularly influenced by the geometry and complexity of the parts. Moreover resulting effects include higher tooth root strengths and higher flank load capacity of the part due to the specific characteristics of the rolling process. Figure 12 demonstrates these effects on the properties of the part.

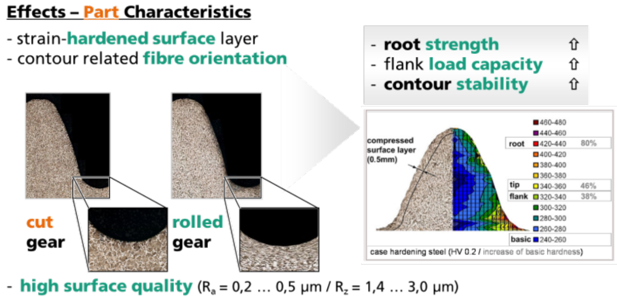

Figure 12 - Improvement of part characteristics.

Figure 13 shows selected examples for gear shafts realized by gear rolling.

Figure 13 - Application of gear rolling for gear shafts.

2.2.4 Constructed crankshaft

Crankshafts for automotive powertrains are still characterized by a relatively large weight. Additionally, the expenditure for machining of crankshafts in the manufacturing process is fairly high in conventional process chains. The amount of chips generated during manufacturing is especially critical when regarding resource-efficient manufacturing.

For these reasons, a joint project with Volkswagen Sachsen GmbH (funded by the European Union and the Free State of Saxony) had the objective of identifying strategies to significantly reduce the weight of crankshafts and also to minimize the machining effort. Within the framework of this project, one approach consisted in the development of a constructed, modularly designed crankshaft. Separate sheet metal parts were used for the cheeks and hollow profile sections for manufacturing the bearings. Figure 14 shows the basic design of a crankshaft module.

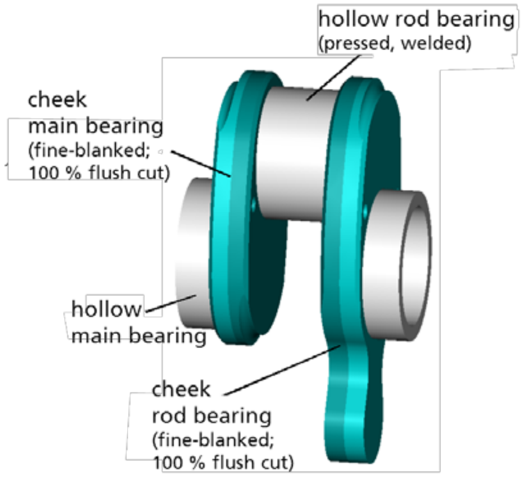

Figure 14 - Design of a crankshaft module.

The first challenge consisted in identifying suitable technologies for manufacturing sheet metal cheeks. The following two variants were investigated:

- two-piece cheek (thickness of initial sheet metal s_0 = 8 mm)
- one-piece cheek (thickness of initial sheet metal s_0 = 16 mm)

Considering the required accuracies and tolerances, the technology of fine blanking was selected and successfully applied for manufacturing the cheeks.

Another challenge was to identify a suitable joining technology for the complete crankshaft. The investigations included welding operations and also mechanical joining processes based on form and / or force fit. The suitable process variant was determined to be a combination of a press-in operation and welding.

Based on this technology crankshaft prototypes were realized (Figure 15). Their fatigue strength and torsional stiffness were comparable to those of serial shafts. Low deficits were detected concerning noise emission.

Figure 15 - Realized constructed crankshaft.

Regarding the specific project objectives, the results of the project comprised a significant reduction of the part weight (17%) as well as considerably less mechanical processing (amount of chips reduced by 75%). Moreover the modular construction offers the potential of manufacturing various part sizes economically.

3 SUMMARY

Today lightweight construction represents a main topic regarding the requirements for reducing the consumption or emissions of CO_2. This paper has discussed hollow shaft concepts for automotive powertrains, which can contribute to achieving these objectives.

In addition to manufacturing these innovative lightweight components, production engineering has to meet other challenges in order to implement these research results into series production. These challenges include, for example, ensuring safe robust process chains or affordable lightweight construction based on efficient forming technologies and forming plants. In this context another important boundary condition consists in the integration capability of hollow shaft concepts into production cycles.

Finally it can be concluded that this challenge requires a holistic view of process chains for producing these lightweight components.

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5 BIOGRAPHY

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Improvement of The Formability of Aluminum Extrusion Profiles by a Tailored, Local Short-Term Heat Treatment

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Abstract

In many industrial fields, especially in the automotive and aerospace sector, aluminum profiles are used for lightweight constructions. However, the formability of aluminum profiles is limited and therefore the production of complex geometries is often challenging. At the Institute of Manufacturing Technology (LFT) an innovative approach to enhance bendability was invented. Key idea of the so called Tailor Heat Treated Profiles (THTP) is a local softening of the material by a short-term heat treatment prior to the forming process in order to improve the material flow. Thereby, in contrast to conventional temperature assisted processes, the forming operation is performed at room temperature and consequently conventional forming tools can be used. For the technology, in particular, aluminum alloys of the 6000 series are suitable, because only a short-term heat treatment is necessary to dissolve the strength increasing precipitations in the aluminum matrix and soften the material. Within this contribution all necessary steps for an effective application of the technology will be presented. Based on a comprehensive material characterization heat treatment layouts will be designed. Finally, guidelines for the design of heat treatment layouts can be derived and verified in experimental bending tests.

Keywords

aluminum, profiles, heat treatment, formability enhancement

1 INTRODUCTION

Since the first serial application of aluminum in the automotive industry in the 1990's a major change of mind has taken place. Aluminum which was mainly used to decrease wear and tear of the tires is now of high importance to reduce the vehicles weight and as consequence cut the overall fuel consumption. The main reason for this approach is the political and social rethinking process with regard to environmental protection. Due to this, laws have been released restricting the maximum permitted CO_2-emission per vehicle. The so called lightweight materials such as aluminum provide a solution to cope with this development [1].

One application of this approach is the aluminum space frame of the Audi A8 which is almost entirely made out of different aluminum semi-finished products. A large percentage of these parts are extrusion profiles, which are frequently used due to their high stiffness and efficient producibility and are mainly processed by bending operations. However, profiles possess only limited formability. This is expressed by premature failure during bending as well as geometrical defects such as warping, buckling, wrinkling and cross section reductions, which result in decreased accuracy and quality. [2]

Up to the present time various technologies have been investigated and refined to improve the formability of aluminum profiles and to prevent the occurring cross section deformations. Solutions for the latter are for example the use of mandrels [3] and fillings [4] to support the profile from the inside. Other approaches focus on the superposition of forces to stabilize the cross section by a combined stretch bending [5]. The task to enhance the formability is clearly more sophisticated and only few approaches exist like for example a directly bending of the profiles after the extrusion process [6]. However, in general these methods are quite costly and inflexible. In the absence of feasible alternatives there is a need for a reasonable and effective method to improve the formability of aluminum profiles.

2 SHORT-TERM HEAT TREATMENT

One innovative technology with the capability to improve the formability of aluminum alloys by a short-term heat treatment is the so called Tailor Heat Treatment (THT). This technology is of high potential to improve the material flow, mainly of the 6000 aluminum series, in the forming process [7]. The short-term heat input causes a dissolution of the magnesium and silicon atoms in the aluminum matrix (Figure 1). As a result the dislocations' mobility is improved leading to a softening of the material. When applied locally, for example by laser radiation, the result is a tailored semi-finished product with soft and hard zones. Thereby the material flow in a subsequent forming process can be purposefully controlled leading to an improved formability.

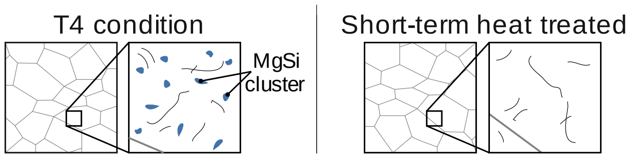

Figure 1 - Microstructural changes

Although this technology already found its way into series production for blank material up till now there is no application of the method to aluminum profiles. Because first bending tests of heat treated aluminum specimens [8] as well as aluminum profiles [9] showed promising results, further research work should be aimed to enhance the bendability of aluminum extrusion profiles. In this publication a methodology with design principles for a successful implementation of the THT technology for aluminum extrusion profiles will be presented.

3 EXPERIMENTAL SETUP

3.1 Material

The research work deals with an aluminum extrusion alloy EN AW 6060 in T4 condition, which means the profile is solution annealed and afterwards naturally aged. The main alloying elements are Mg and Si, having the highest impact on the mechanical properties.

The material is extruded as profiles with dimensions 20x20 mm and a material thickness of 2 mm. The specimens are initially laser cutted with a material allowance of 1 mm in the measuring zone by a Trumpf CO_2-Laser (TruLaser Cell 7020). Consecutively, the specimens are milled to their final dimensions to avoid the influence of the thermal cutting process on the mechanical properties of the material. The standard specimen dimensions are scaled by a factor of 0.7 to fit the profile geometry. This results in a reduction of the standard measuring width from 12.5 mm to 8.75 mm. For the three point bending tests the semi-finished product was mechanically cutted to sections of 120 mm length (Figure 2)

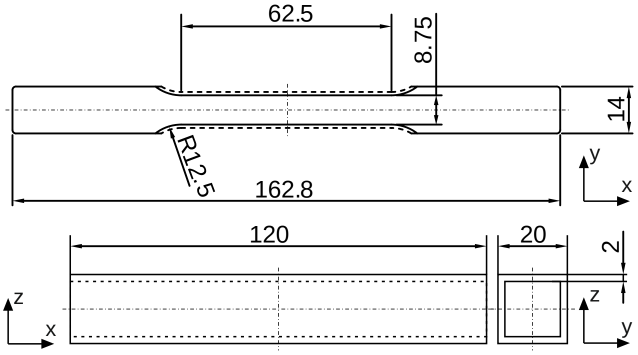

Figure 2 - Tensile and bending specimen

3.2 Heat treatment setup

In general there are three different heat treatment technologies which are worth considering in the field of short-term heat treatment: conduction, induction and radiation heating. Both, conduction and induction heating afford high costs regarding the tool construction and realisation of different heat treatment layouts [10]. Therefore a KUKA robot controlled laser system was chosen for the implementation of the heat treatment, because of its high flexibility and adaptability with regard to the size and dimensionality of the feasible heat treatment layouts (Figure 3).

The laser source is a Nd:YAG crystal, producing a maximum output power of 4 kW and possesses a Gaussian intensity distribution. Because of the short wave length of 1064 nm laser beam guidance by optical fibers as well as good absorption of the laser irradiation by the aluminum alloy is secured [11]. For the tensile as well as the bending specimens the focus diameter was set to 16 mm and the resulting temperatures were analysed by an infrared camera FLIR SC7600. Before the heat treatment a graphite coating with an emissivity coefficient of 0.95 was applied to the specimens to homogenize the absorption level.

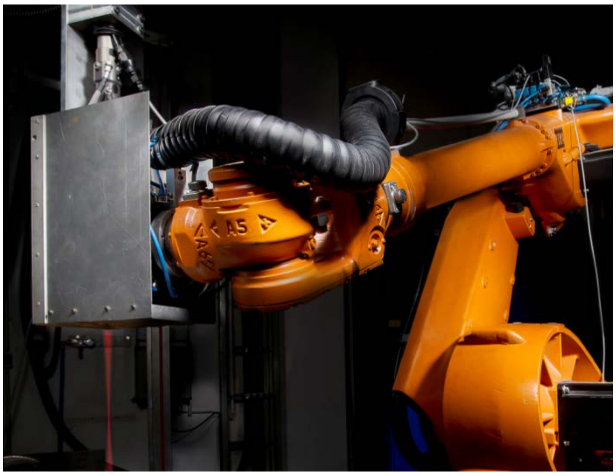

Figure 3 - KUKA robot controlled laser system

3.3 Uniaxial tensile tests

In order to analyse the mechanical properties tensile tests were performed with a Zwick 100 testing machine according to the parameters of the testing and documentation guideline for mechanical properties of aluminum materials in the automotive industry, PuD-Al. During the testing phase the cross head movement is stress-controlled in the elastic zone with 5 MPa/s and afterwards strain-controlled with 0.667 %/s. From the result data mechanical properties depending on the different maximum temperatures were calculated and compared.

3.4 Three point bending tests

For the analysis of the formability three point bending tests were conducted to identify the influence of the heat treatment on the bending characteristics of the aluminum extrusion alloy. In fact the results of this test provide the foundation for the design of heat treatment layouts.

For the experiments a RM400 universal testing machine of Schenck Trebel with the computation software TestXpert of Zwick&Röll was used. The bending setup consists of a punch with a radius of 6 mm and two supports arranged with a distance of 60 mm and radii of 25 mm (Figure 4). The punch is pressed against the profile with a velocity of 1 mm/s until a strength decrease of 10% occurs which signalizes the failure of the profile.

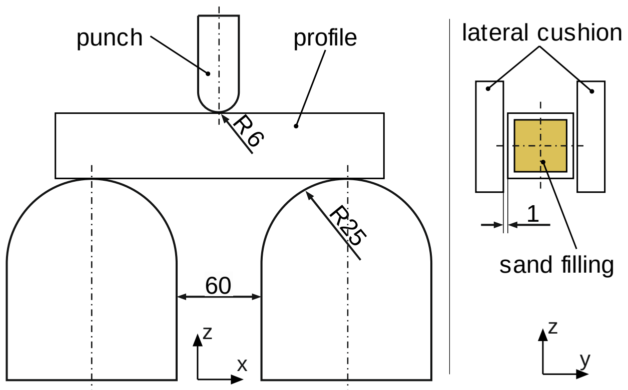

Figure 4 - Three point bending setup

A filling medium was used to avoid undesired cross section collapses of the upper and lower profile wall due to compression stresses. For that purpose, the profiles were filled with quartz sand and sealed by steel plugs at both ends.

In addition, a buckling of the profile appears on the lateral walls. This was reduced by steel plates which were arranged sideways of the profile with a gap of 1 mm. Due to these modifications a cross section deformation is prohibited and the material flow along the profile length is improved. (Figure 4)

4 MATERIAL CHARACTERIZATION

For the identification of the influence of a short-term heat treatment on the mechanical properties of the aluminum alloy EN AW 6060, tensile tests are conducted. Directly after the short-term heat treatment a natural ageing process sets in, that leads to an increase in strength of the material.

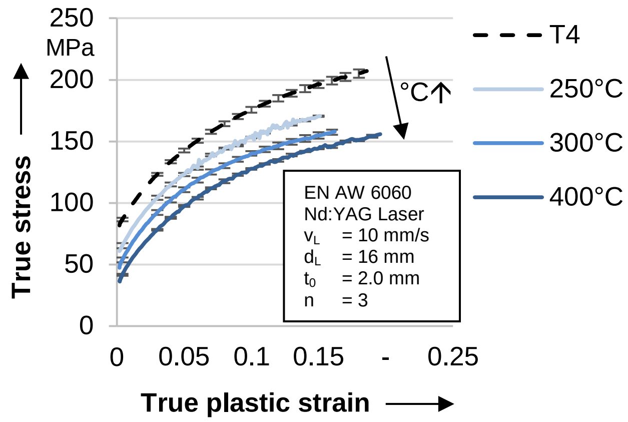

Figure 5 - Stress-Strain curves

Therefore, the specimens are tested in a time interval of 30 minutes after the heat treatment to detect the maximum softening. The laser power levels needed to achieve temperatures from 250°C to 400°C are identified by thermal measurements. In Figure 5 the influence of the heat treatment on the flow curves is presented.

For temperatures below 200°C no softening of the material can be obtained, because the induced energy input is insufficient to solute the Mg and Si clusters. Over 200°C a softening effect sets in, which reaches its maximum for 400°C and leads to a decrease of the yield strength of about 50 % from a mean value of 85.7 MPa to 37.9 MPa. An interesting effect which has allready been investigated and stated in numerous investigations is the decrease of the uniform elongation for a short term heat treatment at temperatures from 250°C to 300°C. This effect can most likely be explained by the formation of different β-precipitations which lead to an early failure of the material. [12]

With regard to the hardening coefficient n an increase of the values can be stated for higher temperatures. The Lankford coefficient R of the material in T4 state is 0.55 (Table 1). This value is a measure for the plastic anisotropy of the material. Values lower than 1 declare that the material thinning is higher than the plane material flow, which leads to early crack formation. This value increases slightly for heat treatments at higher temperatures but without significant tendency.

Table 1: Hardening and Lankford coefficient

	T4	250°C	300°C	400°C
n	0.27±0.01	0.30±0.01	0,31±0.02	0,33±0.01
R	0.55±0.06	0.63±0.03	0.62±0.07	0.61±0.03

On this basis, it can be derived that a temporary softening of the aluminum extrusion alloy EN AW 6060 can be implemented by the use of a short-term heat treatment. For the application in forming processes the highest softening of the material should be realised. This leads to an improved material flow from the heat treated zones to the critical forming zones allready at low force values. In addition the specimens with the highest softening showed no decrease of formability. Therefore a heat treatment temperature of 400°C is mandatory to achieve the best forming result.

5 THTP METHODOLOGY

Key challenge for the application of the THT approach is the design of the suitable heat treatment layout. The material characterization already indicated that the heat treatment not directly leads to an enhancement of the formability. For temperatures between 250°C and 300°C the uniform elongation even decreases. Out of this the question arises, if the effects of the short-term heat treatment can be used to improve the formability. In general, two fundamental strategies are used. On the one hand, a softening of the material can be used to enlarge the forming zone and consequently reduce the maximum strains and avoid a localisation of the thinning (Effect 1). On the other hand based on the earlier plastification of the material the forming forces can be decreased, which results in globally reduced stresses (Effect 2). In Figure 6 a comprehensive methodology is presented, how the two effects can be applied and the technology can be successfully implemented.

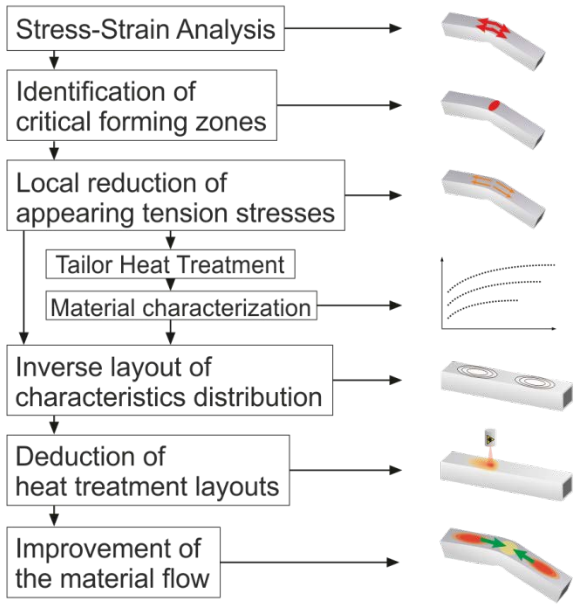

Figure 6 - THTP Methodology

The design of the heat treatment layout starts with the analysis of the stress and strain conditions depending on the process and material parameters, which is depicted in Figure 7. In the case of the three point bending test there are tension stresses on the upper side of the bended profile and compression stresses on the lower side. The transversal forces perpendicular to the bending moment are counteracted by the filling medium and lateral cushions, whereby the cross-section deformation of the profile is minimized. Thus the failure of the profile is caused solely due to the reduction of the wall thickness.

In addition to tensile, also perpendicular strains occur on the upper side of the profile leading to a thickness decrease of the material as well as strains transversely to the extrusion direction resulting in a small cross section deformation, that is limited by the filling medium and the lateral cushions.

After identifying the critical forming zone in the middle of the upper profile wall a local reduction of the appearing tension stresses has to be achieved by a distribution of the strains over a larger area. An improvement of the material flow in longitudinal direction by a local heat treatment is one possible conversion of this objective.

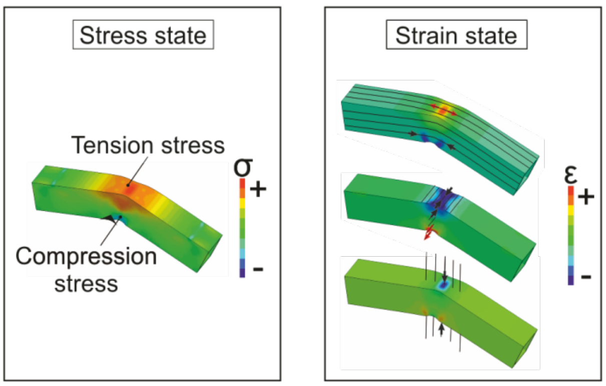

Figure 7 - Stress-Strain analysis

5.1 Design of heat treatment layouts

In Figure 8 three auspicious heat treatment layouts for the enhancement of the formability based on the two main effects are presented taking into account the results from the strain analysis as well as the material characterization. In order to improve the material flow and releaving the critical forming zone, softened zones are arranged on both sides of the profile leaving the middle untreated. Those zones have lower yield strength and due to this plastify earlier in the bending process. The critical forming zone will be releaved and the forming forces as well as the maximum tension stresses are reduced.

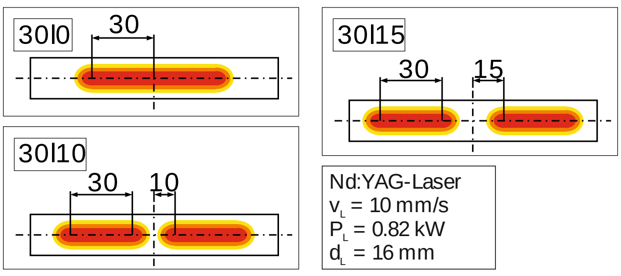

Figure 8 - Heat treatment layouts

Thus, the distance of the heat treated zones to the middle will be varied from 10 mm (30I10) to 15 mm (30I15) in a second approach. In the third approach the profile will be heat treated completely (30l0) to show the influence of a softened forming zone on the bending result.

5.2 Three point bending test

In a preceding step analytical conclusions were drawn from the three point bending test regarding the material flow and bending behavior. As evaluation criteria for the effectiveness of the respective heat treatment layout the achievable bending angles as well as the occurring forming forces are compared with the results of the untreated reference profile (Figure 9).

The bending test with the reference profile leads to displacement values of 20.5 mm and a maximum force of 8.3 kN. As indicated above, the necking appears in the middle of the profile in the critical forming zone. The heat treatment layout “30l0” lead to the lowest forming forces of maximum 7 kN but also the achievable punch movement until failure was lower than the reference profile’s at 18.9 mm.

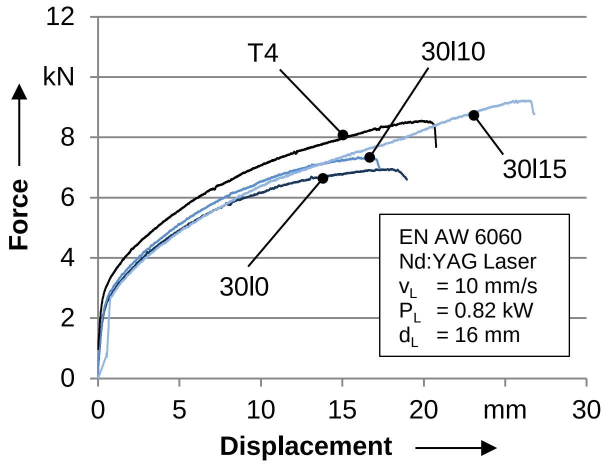

Figure 9 - Force displacement curves

With the heat treatment layout “30l10” the displacement was even lower with only 17.3 mm. The highest improvement of formbality was achieved with the layout “30l15”. A punch displacement of 26.7 mm was reached, which is an improvement of about 30% in comparison to the reference profile.

In Figure 9 the results of the bending tests are presented. Without a heat treatment (a) the stresses are localized directly in the middle of the profile. Only a low bending angle of 20° can be reached. For the profile layout (b) the complete upper side was heat treated. Althought the results from the force-stroke curve indicated that the necessary forces can be reduced, the bending angle even decreases. Main challenge within this context is that the material flow starts earlier, which results in lower forces, but the softening of the forming zone leads to earlier failure.

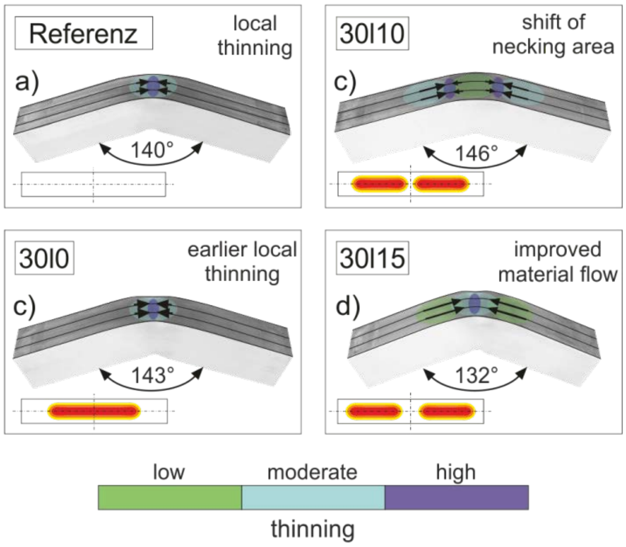

Figure 10 - Material flow and failure behaviour

Consequently the specimen is more susceptible for failure. Other results can be seen for the layout “30l10”. Thereby, the critical forming zone was not heat treated with the intention to stabilize the crack critical area. However, because the softened zones and in particular the heat affected zone with its low formability is too close to the critical forming zone, the material starts necking to the sides of the center (c). Hence, it can be concluded that the formability of the profiles reacts highly sensitive to the position of the softened zones and in particular their distance to the forming area. In this context the layout “30l15” represents a first example for the succesful design of heat treatment layouts for aluminum extrusion profiles. Based on the suitable interaction of soft and hard areas the material flow can be improved and the bending angle can be enhanced.

6 CONCLUSION

Within the research acitivites a new and innnovative approach to enhance the formability of the precipitation hardenable aluminium alloy EN AW 6060 was presented. Extrusion profiles are widely used in the automotive industry in order to realize lightweight constructions. However, the formabiltiy is low in comparison to conventional steel products. Key idea of the so called Tailor Heat Treated Profiles approach is the optimization of the mechanical properties before the forming operation by local short-term heat treatment. In contrast to conventional temperature assisted forming processes the profile cools down completely before the bending operation and consequently conventional tools and machines can be used.

In the context of the investigations all necessary steps for the successfull application of the technology are presented. Within the comprehensive material characterization the influence of short-term heat treatment on the flow behavior was identified. The maximum softening can be reached for a temperature of 400°C. However, for temperatures between 250°C and 300°C a decrease of the uniform elongation was measured. Afterwards the fundamental principles for the design of the heat treatment layout were presented. Key idea is the improvement of the material flow to critical forming zones. In general, the areas with the maximum stresses should not be heat treated, because the specimen would be more susceptible to failure. Based on the results a holistic methodology for the design of heat treatment layouts was derived for aluminum profiles. Finally, the effectiveness of the scientific findinds were validated by real heat treatment and bending tests.

7 OUTLOOK

In the further investigations in general the topics dealt with will be the influence of the size and orientation of softened areas and the expansion of the heat affected zone on the formability of aluminum extrusion profiles. In particular the realisation of three dimensional heat treatment layouts and its effect on the thinning of the material will be identified. In addition the results of the investigations will be used as a base for the development of numerical simulations to improve the design of heat treatment layouts. Finnally, additional precipitaiton hardenable aluminum alloys will be investigated in order verify the transferability and generality of the results.

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Toward Understanding the Process Limits of Incremental Sheet Forming of Titanium Alloys

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Abstract
Incremental sheet forming (ISF) process is characterised by high flexibility at low cost, and short replacement time. ISF as a process has received global attention. Particular areas include the aerospace industries, customized products for biomedical applications and prototyping in the automotive industry. Most applications can become competitive due to the flexibility offered by this manufacturing process. In this work, a background study and review of state-of-the-art ISF have been undertaken with the aim of providing a better understanding of the process limitations. The critical factors of incremental sheet forming were discussed and the mechanical and thermal process demands were identified. This information provides the foundation for developing a forming optimisation map.

Keywords
Incremental forming, forming demands, process limits

1 INTRODUCTION

Innovative technologies of forming sheet metal are now at a stage where it is possible to produce either custom parts or small batch production quantities, with very short turnaround times from design to manufacture [1]. ISF process is characterized by high flexibility at low cost, and short replacement time. It allows for making of 3D complex sheet parts, while requires an available computer numerical control (CNC) machine, a simple rig, and universal tool. Thus, it is well - suited to meet agile manufacturing requirements for sheet forming of one-off component, prototyping or small production runs.

The ISF process makes use of a simple forming punch with its motion usually defined in terms of Cartesian coordinates [2]. ISF techniques can be distinguished into 'with-die' or 'without-die' also classified as positive and negative forming, respectively [1]. Although the ISF process can be die-less, it does need a backing plate to create a clear change of angle at the sheet surface and improve accuracy. Design changes, which may occur after initial design, can also be easily accommodated, giving the process a high degree of flexibility [3], [4].

The size of a component is rather limited by the working space of the machine than by forming forces. This is because forming forces do not increase since the contact zone and incremental step size remain small. There is also the possibility that the surface finish of the component can be improved [5].

ISF components can be used in minimally invasive surgery (MIS) and customized products in biomedical applications [6]. In the automotive industries ISF can be used in prototyping and conceptual modelling. Aerospace industries frequently require prototypes, and unique or small batches of components too. Other possible uses for ISF can be found in scoops for mining vehicles, water collection gutters, architectural components, and emergency air supply ventilation systems.

2 CRITICAL FACTORS OF INCREMENTAL SHEET FORMING

Incremental sheet forming is a relatively clean and efficient manufacturing technology, with the only waste typically resulting from the lubrication strategy. In most ISF operations, the lubrication fluid can be re-used and there are also no vapours or chips. Table 1 illustrates the ecological benefits using ISF technology for the forming of sheet components. The technology has low energy requirements, as the material is cold-worked with lower forces than used for hydroforming and conventional press using dies. Less energy-intensive machines can therefore be used. Results from published research [7], [8] showed that ISF has many advantages for prototyping and small batch production up to 300 parts from an environmental perspective.

Table 1- Ecological benefits of using the ISF process to form small batch [3].

Ecological benefit	Energy saving	Material saving
No die required	X	X
Reduction of transportation	X	

Reworking instead of reprocessing or scrapping	X	X
Lower forming forces	X	
Smaller machines	X	X

The process is suitable for unique products that are usually manufactured in small batches. High-volume production becomes economically unviable, as illustrated in Figure 1.

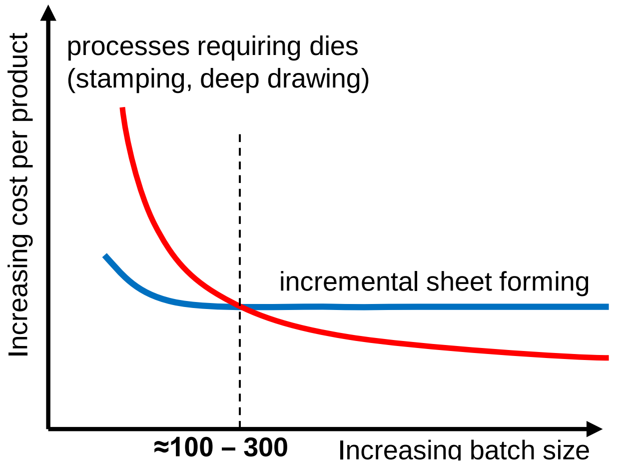

Figure 1- The inverse relationship between batch size and product cost, for ISF and traditional sheet forming (Not to scale – for illustrative purposes only) adapted from [3].

Compared to traditional forming processes that requires dies ISF products become expensive with large batches as each component is individually formed. As the time and cost to produce a die is absorbed with larger batch sizes, the cost and speed per product becomes more feasible with traditional forming processes.

Interesting to note is that as the part complexity increases (more features), the viable batch size when using ISF technology also increases. Knowing this, it is also important to realize that there can be a loss of accuracy with the ISF process, when compared to the stamping of large batches [9]. Therefore, it is not easy to estimate the exact break-even batch size, without doing experimental studies. Another drawback of the ISF process is that the cyclic-time is much longer than competitive processes such as deep drawing. Therefore, the process is limited to small size batch production.

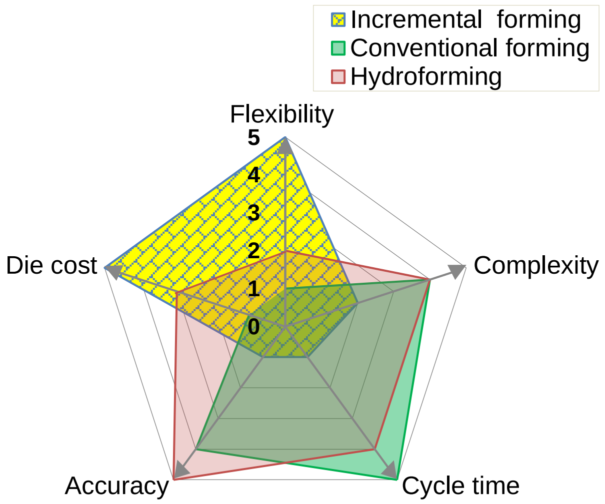

Figure 2- Conceptual comparison of different sheet forming technologies [8].

Figure 2, conceptually paints a comparison between ISF, hydroforming and conventional forming, using five weighting aspects (process flexibility, costs of required dies, processing time, and complexity of formed component and produced accuracy).

Evaluations from 1 for (poor) to 5 for (very good) are assigned to each of aspects mentioned. As it highlighted on the figure, every technology has its own strength and weaknesses. They cannot replace each other in all applications, however, trade-offs between them always exist [8].

Due to the applied tension stresses, sheet metal forming processes are limited by instability (necking), namely localised deformation over a small area (neck), while the adjoining area of the sheet stops deforming and any further stress will create a large strain, leads to sheet failure [10].

The analysis of deformation in sheet metal forming is often based on two principle membrane strains, ε_1 and ε_2. Most often, the maximum principle (major) strain, ε_1 is positive for the forming operation. The defination of positive and negitive strains are illustrated in Figure 3(a).

In the sheet metal industry the representation of the in-plane strain state, known as the forming limit diagrams (FLDs), together with forming limit curves (FLCs), are widely used to assess material formability and part manufacturability [11].The FLC in Figure 3(b) limits the boundary between the safe forming zone and the material plastic instability zone above the curve. Hence, the state of strain in forming must be such that it falls below the curve for particular material.

Practically, FLDs and FLCs are valid subject to certain restrictions, amongst others: a straight strain path (proportional loading); the situation of plane stress; absence of bending; and absence of through thickness shear [12], [10].

For ISF the relationship between strain limits plot on a straight line with negative slope in the area where minor strain $\varepsilon_2 > 0$. As shown on Figure 3(b), at a particular value of ε_2, (when $\varepsilon_2 > 0$), ε_2 for FLC-ISF (blue dashed line) is significantly larger than typical corresponding limit predicted for FLC as applicable to conventional forming processes, and close to material fracture limit [12], [13]. Previous studies on the morphology of the cracks and analysis of thickness variation of ISF formed components, revealed that material deforms by uniform thinning until fracture, without developing of necking [13]–[15].

It has been postulated that the extremely small deformation region as compared to the sheet size, leads to a plastic zone always surrounded by elastic material that effects the development of necking.

Furthermore the combination of: serrated strain baths arising from cyclical, local loading; dynamic bending and unbending under tension of sheet around the forming tool; stretching; and through thickness-shear, are proposed to describe these special forming conditions that lead to stabile deformation and the suppression of sheet necking [12].Therefore, all the above-mentioned forming conditions to generate a FLD are violated in ISF.

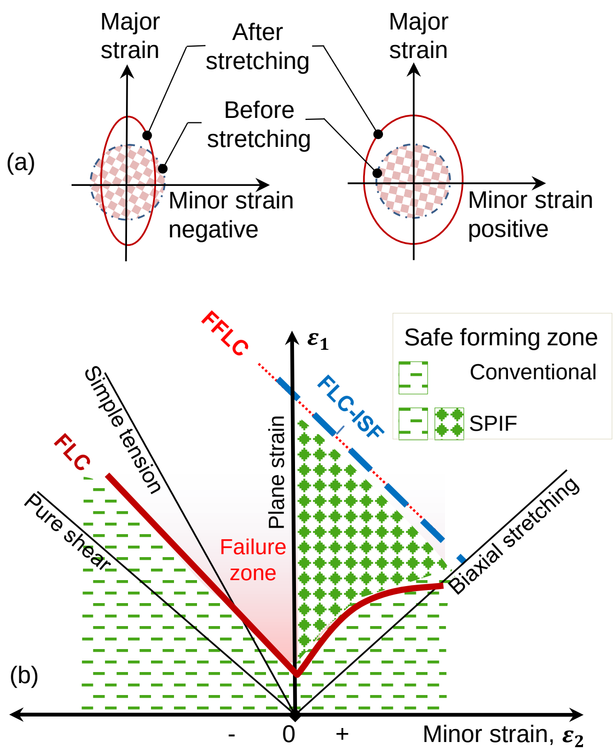

Figure 3- Schematic presentation of the principal strain space showing: (a) the definition of positive and negative strains [16]; (b) the necking limit (FLC), the fracture limit (FFLC), extended strains in ISF

Consequently, standard FLDs and FLCs of sheet metal, which presume necking as the failure mode, are inapplicable to assess the instability and describe failure in ISF process. Instead, formability limits by fracture and fracture forming limit curves (FFLCs) are recognized as characteristic of process formability and predicting material failure [15], [17].

The large reachable levels of strain before fracture in ISF has been regarded as very beneficial for the environment and cost saving. It enables using of less sheet material and still being able to manufacturing required component, makes ISF more appropriate for processing of high cost lightweight alloys. This is also characterized by the so-called buy-to-fly ratio or the relationship between the money invested for the resources of a certain product and the price of the final product [8], [18].

3 RESEARCH METHODOLOGY

ISF entails process variations and differing equipment configurations. Among these, single point incremental forming (SPIF), utilising three-axis CNC machine tools, appears to be the most flexible, simplest, and low cost approach. However, more efforts need to be directed at improving process accuracy and utilising its potential on a broader scale for manufacturing applications. Authors' main interest is focussed on investigating the capability of the SPIF process in the forming of medical implants, using titanium alloy sheets and a triple-axis CNC milling machine.

As illustrated in Figure 4, a background study and review of state-of-the-art ISF have been undertaken with the aim of providing a better understanding of the process limitations. In this review and background study, significant data on each forming condition from more than 100 relevant research articles and studies were analysed and documented.

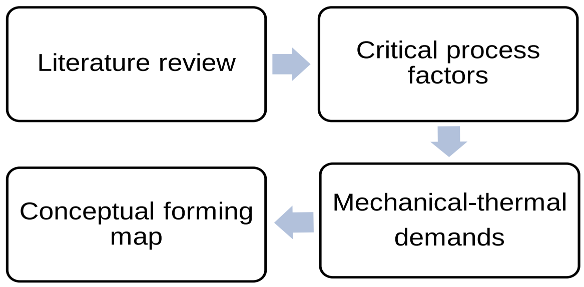

Figure 4- Schematic roadmap of the sequential steps of the applied Research Methodology.

Suitable values and their process limits for the various operating factors and parameters were obtained and summarised from both the abovementioned review and background study.

In selecting these values and their limits for the various parameters, the following conditions were set. It must satisfy: the maximum wall angle (θ_{max}), the minimum load, and good surface quality requirements. Taking account of the conclusions presented by several authors, the suggested optimum values together with their applicable upper and lower limits will be used in order to focus the number of experiments required. Using this data narrows the space when characterising SPIF design factors. This information provides the foundation for developing a forming optimisation map.

4 MECHANICAL AND THERMAL DEMANDS

Unlike in traditional forming technologies, the forming forces in ISF operations are not preselected by the designer or the operator. Instead, forces are generated as a reaction to (or a consequence of) the forming operation. These loads are determined to a large extent by the applied forming strategy, the process kinematics and tool/sheet interaction [19]-[21].

4.1 Mechanical demands

The type and thickness of a material have a direct bearing on its mechanical properties and deformation behaviour during forming. Selecting range of working parameters, loads generated, and thickness of final product all are subjected to the initial thickness and strength of its material. Figure 5 highlights the common range of sheet thickness and types of materials as sourced from the literature. The majority of these materials are soft and ductile metals, like aluminium, particularly the 3xxx series, and deep drawing steel. Some studies included forming of hard-to-form alloys, for example titanium, and titanium alloys, stainless steel, magnesium and high strength-aluminium. Few other studies also uncovered the possibility of expanding the materials capability window of SPIF beyond metals, such as forming of polymer plates [22].

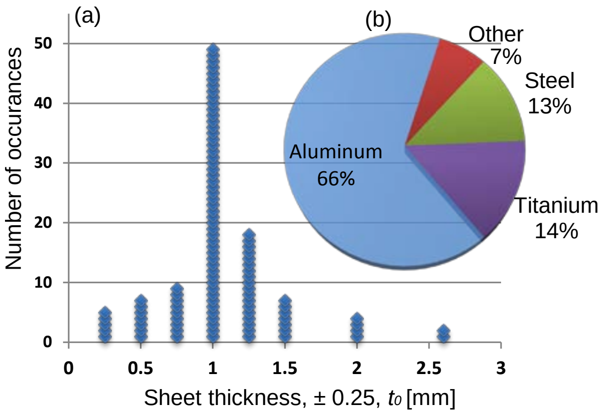

Figure 5- The occurrence of (a) sheet thicknesses, and (b) type of material commonly cited in the literature [2], [5], [7], [9], [13]–[15], [17], [19]–[21], [23], [26]–[110].

Although the ISF process requires high formability, it must be noted that the suitability of this process to effect deformation, is clearly associated with material type used. Forming loads are strongly depending on formed material strength and thickness. Also, the maximum wall angle θ_{max} that can be achieved in single-stage forming of high-strength metals such as titanium, remains lower than 45°. For aluminium and mild steel on the other hand, this angle exceeds 75°.

A strong relationship exists between formability and initial sheet thickness, t_0; matching a suitable tool-tip diameter to the sheet thickness used, rendered the best results [29], [45], [56]. If however the sheet thickness is increased without adjusting the tool-tip diameter, forming loads will also increase [53], [85].

The material of which tool is made, is of crucial importance due to the severe tribological interaction during the ISF process, where tool-tip is in continuously sliding contact with the sheet. High mechanical and thermal loads at the tool/sheet interface cause tool deterioration and premature wear. Thus far carbide, high speed steel, and cold-workable tool steel hardened and tempered to 60 HRc, have been found to exhibit sustained high mechanical and thermal stability, making them suitable materials for tool-tips. Their strength and wear resistance allow them to maintain their forming surface for a longer time [111]. However, for biomedical use, like body parts, contamination of the surface of the component by chemical elements harmful to health (such as Mn, Si, Ni, and Cr) may occur [112]. Thus, a new tool-tip material, which is compatible with health requirements, needs to be identified. Titanium might be a suitable material.

The diameter of the tool-tip, $\emptyset_{t,}$ has a pivotal role in affecting several process aspects like deformation, forming loads and processing time. Small tool-tip diameters increase material formability and generate minimum loads, while dramatically increasing forming time. They produce rough surfaces and exhibit reduced stability under severe forming conditions. Moreover, very small diameters result in material squeezing out from under the tool/sheet contact zone, causing penetration of tool into the sheet and removal of material from work piece surface [45], [113].

By contrast, large tools distribute stresses better over the contact area, reduce processing time and produce a more desirable surface quality. But they significantly increase forming loads. In the production of satisfactory work, there is a strong relationship between tool-tip diameter, $\emptyset_t$ used, and the initial sheet thickness, t_0 [14].To maximise formability and avoid the evolution of forming defects, the appropriate $\emptyset_t$ can be selected so that the threshold ratio, $\emptyset_t/t_0 > 4.7$ [45].

As per the collected data from the literature and depicted in Figure 6, the range of too-tip diameters predominantly applied are between 8 and 15mm.

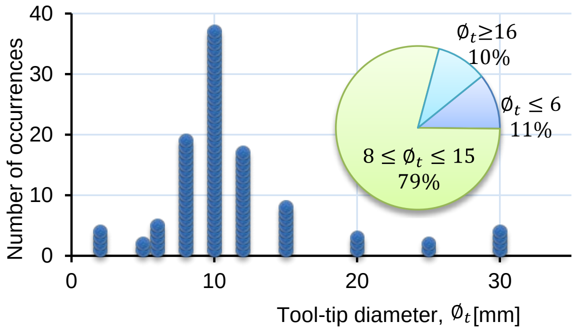

Figure 6- The occurance of tool-tip diameter, $\emptyset_t$, cited in the literature [2], [5], [7], [13]–[15], [17], [19]–[21], [23]–[50], [52]–[110].

In the process of forming, the magnitude of the forming loads acting on a sheet surface is dependent on the relative position of tool-tip to the plan area of the sheet, as well as the nature of the tool-tip/sheet interaction. In ISF, trajectories of the forming tool are defined by numerical control codes generated by a CAM system, based on the CAD model or target geometry. Standard helical and contour milling toolpaths are frequently adopted when performing ISF. Using helical tool paths generates surface qualities better than from simple z-level contours. The latter leaves marks (scarring) on sheet surface and causes force peaks [47], [55]. Other important factors related to ISF toolpath design are listed below.

Step depth is the vertical distance (Δz) between successive contours or is the amount of material deformed for each single pass of the forming tool. The step depth is comparable to the depth of cut in machining. It is selected mainly with regard to $\emptyset_t$ of the applied tool-tip, the target shape and the demands of surface quality. The interaction of step depth and tool-tip diameter significantly affects the formability process in terms of the generated loads at tool-tip, execution time, and produced component quality. In general, large Δz substantially reduce processing time. However, when using small tool-tips, a high surface roughness occurs [26], [28]. Furthermore, a large Δz implies large deformation of the sheet on each pass, and so intensifies the forming forces due to the extension of the tool/sheet contact area [88]. Figure 7 displays experimental values of Δz, as found in the literature consulted. The figure highlights the range of Δz most frequently used is form 0.25 – 0.5mm.

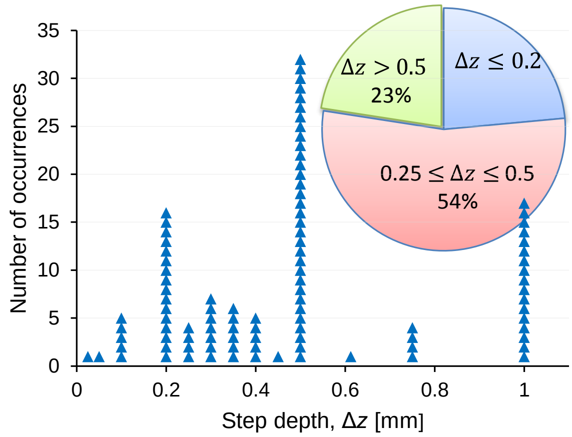

Figure 7- The occurrence of step depth, Δz, cited in the literature [2], [5], [7], [13]–[15], [17], [19]–[21], [23], [26]–[55], [57]–[84], [86]–[110], [112]–[116].

4.2 Thermal demands

Elevated temperatures are an enhancing factor in metal forming. They help soften the work piece material, reduce the required loads, and minimise springback. In different conventional metal forming operations, particularly, when forming of lightweight alloys, thermal energies from external sources are usually integrated with mechanical loads in at least one stage (before, during or after) the forming process, to increase formability and relieve residual stresses. And ISF is no exception, as the researchers have developed few hybrid versions of the ISF process referred to as heat-assisted incremental forming. In this heat-assisted process, localised dynamic thermal energy from an external source is applied and integrated into the forming zone; the energy is either from a high ampere DC current running through the forming tool onto the sheet, so-called electrically-assisted forming [8], [30], [46], [110], or from a directed laser beam, referred to as laser-assisted forming [45], [47], [102], [115], [116]. Applying external energy to the forming zone leads to significant benefits in terms of increased formability and a decrease in the forces required, however in expense of process complexity and increased cost.

Conversely, in cold SPIF operations, too much heat due to friction could lead to negative effects on the forming tool or workpiece surface at the contact zone. Oxidation of formed surface, tool failure due to deflection, or severe wear of the tool, and evaporation of the lubricant are all the major concerns.

The scope of this research is limited to studying of process demands of SPIF at room temperature. The thermal demands considered are only those related to heat generated due to tool/sheet interaction and plastic deformation.

In SPIF heat is generated at the contact zone due to relative motion between tool-tip and work piece surface. Unlike mechanical loads, the effects of thermal loads can to an extent be controlled by tuning the process parameters, so that formability is only marginally affected [58].

Considering friction heat generated in SPIF operations, tool exposure and its speed are the main influencing factors. Forming speed or simply speed, V_f, is the rate at which the outer edge of tool-tip moves along the tool-tip/sheet interface (this is similar to cutting speed in machining). Equation 2 designates that, V_f m/min is directly proportional to tool-tip diameter and its rotation speed. By adjusting spindle rotation ω_t controls the heating of contact zone.

$$V_f = \frac{\pi \cdot \emptyset_t \cdot \omega_t}{1000} \tag{1}$$

As shown in the diagram of the tool/sheet interface in Figure 8, during the course of deformation only a fraction of tool-tip is in direct contact with sheet surface. The tool/sheet interface area can be simplified as a ribbon of constant width.

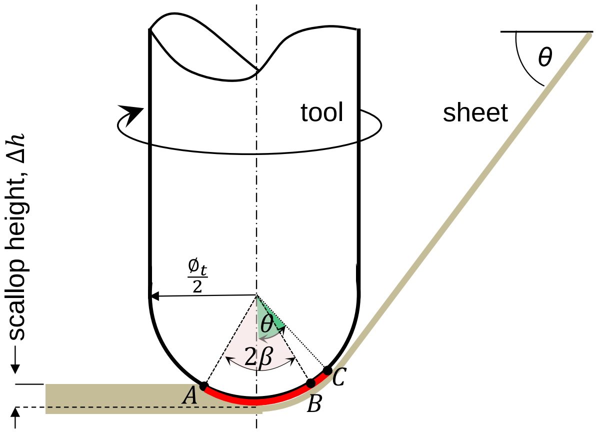

Figure 8- Enlarged diagram of tool/sheet interface

Length of the ribbon l_c equals the arc length $\widehat{ABC}$ is function of tool-tip diameter and two angles in meridional direction; the wall angle, θ ; the half-angle of groove β also known as scallop angle.

$$l_c = \frac{\emptyset_t}{2} \cdot (\theta + \beta) \tag{2}$$

The tool-tip/sheet contact area (tool exposure), is found to be mainly affected by the tool diameter, and to a lesser degree by wall angle and scallop angle which is a function of step depth Δz [15], [33].

In SPIF, different values of tool feed rates, f_t, are testified to have only minor effects on the finish of the sheet surface, the thickness distribution, or the material micro structure of the formed component. Thus, employing high feed rates can considerably reduce manufacturing time without materially affecting component quality, making SPIF more attractive to manufacturing. Figure 9(a) shows the range of process feed rates from the cited references. It is presumed that the upper limit of the practical forming rate is governed by the maximum feed rate achievable by the CNC machine [5], [27], [45]. Of course the rigidity of applied machinery and its tooling setup are critical variables and could be regarded as limiting constraints.

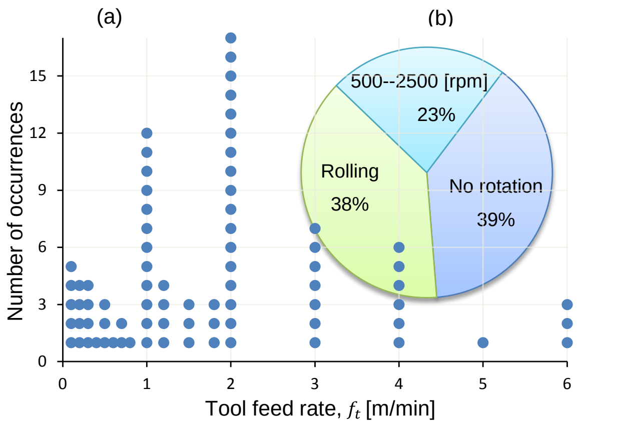

Figure 9- The occurrence of (a) feed rate, f_t , and (b) tool rotation, ω_t, cited in the literature [5], [7], [14], [15], [17], [19]–[21], [23], [26]–[30], [32], [34]–[44], [47]–[51], [53]–[59], [61]–[65], [67]–[73], [75], [77]–[80], [82], [84]–[86], [88]–[100], [103]–[105], [107]–[110].

The mechanism of interaction between tool-tip and sheet is of the utmost importance. As illustrated on Figure 9(b), based on the assigned spindle speed (ω_t) the following four varieties of tip/sheet interactions have been explored in the cited literature:

Fixed tools indent the sheet without rotation; indenting the sheet without rotation increases the heat generated at sheet surface due to sliding friction, and contributes to better formability. However, extreme sliding friction creates high bending loads on the tool-shank, and the applied equipment; raises the generated heat, which increases the wear and surface degrading at the tool-tip; and lowers surface quality.

In another way of interaction, forming tool rolls over the sheet surface with almost no sliding, and deformation occurs by the imposed forces and the rolling friction. This reduces both the relative motion between tool-tip and work piece, as well as the heat generated at the tip/sheet interface. Though, it employs using of inventive tool with freely rotating hardened sphere as tool-tip and pressurised fluid to operate, thus, increases tooling cost [40], [117].

For typical tools with hemispherical head, rolling interaction requires the feed rate to be equal to average edge of tool in contact with sheet multiplied by the spindle speed. As described by Equation 1, the optimum rotational spindle speed, ω_t , is proportional to feed rate, f_t, the tool radius $(\frac{\emptyset_t}{2})$ and wall angle θ of the component being made [1].

$$\omega_t = \frac{f_t}{\pi \cdot \frac{\emptyset_t}{2} \cdot \sqrt{\frac{1}{2}(1 - \cos(2\theta))}} \tag{3}$$

Another widely used interaction employs free (un-driven) tool movement, which leads to a reduction of slide friction, bending and horizontal loads. When generated friction at tool-tip escalates, tool responds and upholds the load by passive rolling over the sheet.

In contrast, while tool-tip moves onto the sheet, the high tool rotation ω_t, reduces friction forces. At very high ω_t, however, the tool slides more often on the same point. The occurring hot forming phenomena can result in chemical attrition at the tool/sheet contact zone [27], [58].

4.3 Towards understanding process demands

Manufactring process must exhibit a feasible space of operating conditions, often referred to as the “Process Window”. A conceptual process window is shown in Figure 10. The illustrated window identifying several process concepts of the SPIF process for two main process states; X_1 and X_2.

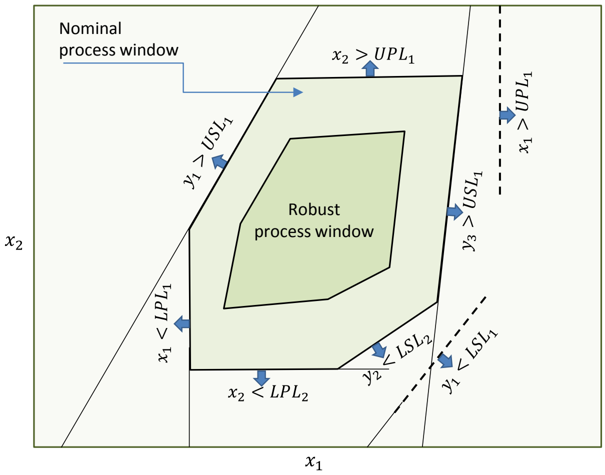

Figure 10- Process map formation (adapted [117])

Each one-sided constraint applied to either a process input (design variable), x_i or quality attribute, y_j, eliminates a region of the process from the overall process operating space. The process outputs, y_i, may also be modeled as a function of x_i in process objective function, $f(x_i)$. In the optimisation process, the goal is to minimise the objective function, $f(x, y)$. Subject to a set of constraints in the region of interest:

$$\begin{gathered} LPL_i \leq x_i \geq UPL_i \\ LSL_j \leq y_j \leq USL_j \end{gathered} \quad (4)$$

Where; LPL_i and UPL_i are the lower and upper process limits for the process design variables, x_i, LSL_j and USL_j are the lower/upper specification limits for the process outputs, y_j [117].

Establishing SPIF process window is complicated and requires characterisation of operable range of several interacting process factors.
Process non-operable boundaries are usually identified using the DOE, which can be very demanding in time and resources. The adequate operating region for the process factors can be narrowed from identified process characterization. A proposed method will employ the data documented from previous work in literature as references when characterising of feasible region of SPIF. Therefore allows future research to be focused on process optimisation and high model fidelity inside the characterised space.

5 CONCLUSION

In this work, an extensive review of state-of-the-art ISF was conducted on the data from previously accomplished research efforts. This data has been classified and documented. The documented data and acquired knowledge will then be employed as references when characterising the SPIF key design factors and their variable limits.
In this paper, wherever possible, these limits and their effect on SPIF have been visually presented in the form of charts and tables, with related deductions and conclusions provided in the adjoining text.
Tool-tip diameter and step depth (as adjustable variables) together with sheet thickness and wall angle (as geometry dependent variables) were understood to be the main design factors in the planning for SPIF processes.
In addition to their individual effects, the role of the interaction between these variables needs to be considered. Alternation of the horizontal and rotational speeds has a minor impact on the magnitude of mechanical loads, but it significantly changes the thermal loads. A high feed rate is favourable for improving execution time and a high rotational speed reduces sliding friction and enhances the quality of formed component.

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Numerical Investigation for Superplastic Forming Tool Development within the Combined Process Chain of Forming and Additive Manufacturing

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Abstract

Key motivation behind the combination of superplastic forming and additive manufacturing is to merge the advantages of two different manufacturing methods. On the one hand the efficiency to form large scaled parts by superplastic forming and on the other hand additive manufacturing of highly customised products. While the combination of additive manufacturing with bulk structures is state of the art, combining sheet metal parts with additive functional elements is hardly investigated. Few research works have been published regarding additively manufactured functional elements on deep drawn sheet parts. As forming is limited for Ti-6Al-4V at room temperature and even at moderate temperatures, this paper presents a new and innovative manufacturing process chain, where superplastic forming and additive manufacturing is combined to merge the advantages of both. Within this work the possibilities of additive manufacturing on sheet metal is presented in addition to the numerical simulation of superplastic forming of Ti-6Al-4V to produce a semi-finished sheet part for subsequent additive manufacturing process. As a result of this study a LS-DYNA based numerical model is presented for tool development as well as process simulation for superplastic forming of semi-finished parts which can be utilized for consecutive additive manufacturing operation.

Keywords

Superplastic Forming, Additive Manufacturing, Ti-6Al-4V

1 INTRODUCTION

Titanium and its alloys are commonly utilized materials for engineering applications [1]. This fact is due to a wide range of positive characteristics of titanium for industrial parts. First of all, titanium has a significant strength combined with low density, good weldability and corrosion resistance [2]. Furthermore, it reveals an outstanding bio-compatibility and a young modulus comparable with human bone structure [3]. The most significant titanium alloy is Ti-6Al-4V, with 50% share of the worldwide titanium production [4]. Because of its advantages, this alloy is used in a lot of industrial applications. First of all, titanium alloys such as Ti-6Al-4V are used in the medical industry for spinal disc replacements, knee implants, screws for the fixation of medical parts [5]. Secondly, in the field of aerospace turbine blades, external shells for turbines and landing gear components are manufactured of titanium and its alloys [6]. In addition, parts for chemical and automotive industry such as pump components and valves are represented by titanium alloys [7].

To create parts out of titanium, a wide range of manufacturing techniques are industrially applied. While casting, welding, forming and machining are traditional and well established techniques to give titanium the desired shape, a new manufacturing method is additive manufacturing. For additive manufacturing of Ti-6Al-4V, electron and laser beam melting are the most utilized processes in industrial use [8]. Both techniques are characterised by the ability to produce near-net-shaped [9], fully dense 3D structure directly from digital data by selectively melting micro-sized metal powder using a high intensity energy beam [10]. In addition to the reduction of material wastage by producing near-net shape parts, unique geometries and individual parts can be achieved [11]. Negative aspects of additive manufacturing include long process time and geometrical limitation regarding the maximum final part size [12].

Another industrial relevant forming technique is sheet metal forming, which is characterised by low process time, large scaled parts and low cost for mass production [13]. When forming titanium alloys one of the great challenges is formability restriction due to low formability at room temperature [14]. To overcome this limitation, forming of titanium alloys is fulfilled at elevated temperatures. Temperatures of up to 600 °C enable traditional sheet metal forming and increase the forming limit constantly [15]. Distinct increase of the forming limit can be achieved by superplastic forming [16]. When utilizing low strain rates and temperatures of 925 °C, the so called superplastic forming condition is dominant with presence of low stresses and high formability of up to 500 % [3].

A variety of microstructural mechanisms have been reported for superplasticity including slip, diffusion or dislocation creep and grain boundary sliding [17]. Necessary conditions for superplastic behavior are a stable fine-grained microstructure with a grain size of typically 10 µm and a temperature higher than half of the melting temperature [16]. If these conditions are fulfilled, superplastic forming enabling tremendously increased forming limits is feasible. However, the control of the forming process parameters is important to reach the full potential of this forming operation. To overcome the individual disadvantages of both manufacturing techniques and combine the strengths of both, their combination within a single hybrid process chain is presented in this paper.

2 PROCESS CHAIN TO COMBINE ADDITIVE MANUFACTRING AND SUPERPLASTIC FORMING

The new process chain to achieve parts which are manufactured by the combination of forming and additive manufacturing is visualized in Figure 1.

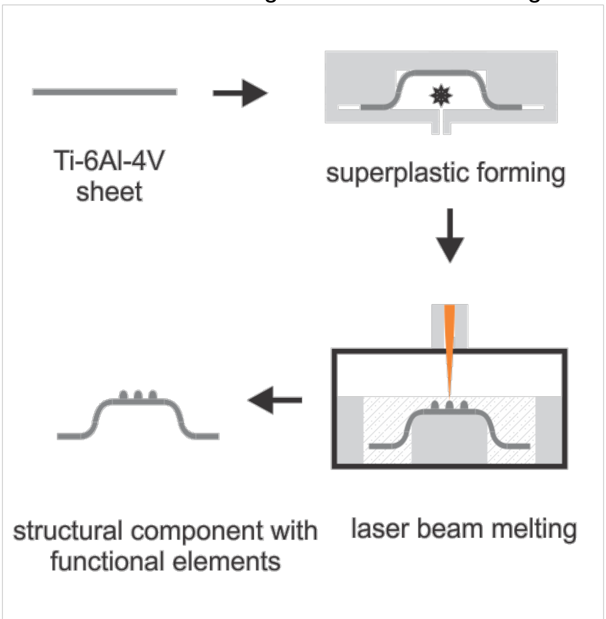

Figure 1 - Process chain for combination of superplastic forming and laser beam melting of Ti-6Al-4V

First of all, the initial Ti-6Al-4V sheet metal blank is formed to a semi-finished cup by superplastic forming. Afterwards functional elements are created by additive manufacturing employing laser beam melting to achieve the final structural component consisting of a sheet metal body with functional elements out of the same material. Within this hybrid process chain, the large dimension basic geometry is manufactured by superplastic forming. As a result large scaled parts can be achieved with low processing time compared to purely additively manufactured ones. Possible application for these parts could be utilized in the aerospace or medical industry. One possible part could be fixation plates produced in a way where most of the part volume is formed and then equipped with individual and functional fixations or surface elements.

3 ADDITIVE MANUFACTURING AND MECHANICAL CHARACTERISTICS OF ADDITIVE MANUFACTURED PARTS

For the combination of forming and additive manufacturing the limits and possibilities of additive manufacturing of Ti-6Al-4V as well as the final material characteristics require fundamental understanding. Both electron beam melting as well as laser beam melting are capable to process Ti-6Al-4V [18]. Ahuja et al. [19] presented research work where process parameters have been developed for Ti-6Al-4V with a grain size between 20 µm and 50 µm manufactured with a Realizer SLM 50. Cylindrical bars have been manufactured and tested according to DIN EN ISO 6892-1 [20]. The resulting mechanical characteristics prove a high yield strength and an ultimate tensile strength with values of about 1300 MPa and 1400 MPa [19]. These results are comparable with experimental investigations of Vrancken et al. [21] Further Schaub et al. [22] investigated mechanical characteristics of selective electron beam melted parts out of Ti-6Al-4V manufactured with an Arcam S12 SEBM-machine. Resulting mechanical characteristics are of high quality with yield strength up to 1024 MPa and tensile strength up to 1079 MPa. In comparison to laser beam melted parts the electron beam melted do not require post heat treatment, as those parts are processed at elevated temperatures.

All reported research work proves good mechanical characteristics for both laser and electron beam melted parts. Compared with the mechanical properties of Ti-6Al-4V standardized in DIN 17862 [23] with a minimum yield strength and an ultimate tensile strength of 870 MPa and 920 MPa, all parts exceed these values.

4 ADDITIVE MANUFACTURING COMBINED WITH BULK OR SHEET PARTS

For bulk parts it is state of the art to use additive manufacturing methods [24]. Turbine blades out of Ti-6Al-4V are repaired by using Laser cladding to replace material or fill groves [25]. Challenging for the application of additive techniques on sheet metal is the low mechanical stability of the shape of sheet compared to bulk parts. Current research work is dealing with challenges of additive manufacturing using plates with a thickness of 6 mm or more [26]. This is the reason why only few results can be found for the combination of sheet metal and additive manufacturing and even less for sheet metal forming combined with additive manufacturing. Fundamentals of laser and electron beam melting on initial, flat Ti-6Al-4V sheet have been presented by Schaub et al. [27; 28], Juechter et al. [29] and Ahuja et al. [27]. An approach for laser beam melting of cylinders on formed Ti-6Al-4V sheet has been presented by Ahuja et al. [30]. Within that publication a process chain is shown where Ti-6Al-4V sheet with a thickness of 1.0 mm is formed by deep drawing at 400 °C and, transferred to a laser beam melting set up, clamped with an especially developed tool system and then equipped with functional elements by laser beam melting. Further options such as heat treatment and geometrical design are investigated to improve the mechanical properties of the final part. The resulting strength tested with a hybrid part consisting of 1.5 mm sheet with Ø 5 mm cylindrical functional element has been presented with high mechanical sheer strength of about 580 MPa [30]. These results prove a high potential for hybrid parts manufactured by combination of laser beam melting and sheet metal forming. Nevertheless, the combined process chain of sheet metal forming at elevated temperatures and additive manufacturing has distinct limitations. These are related to the sheet thickness, residual stresses and shape deviation of the semi-finished sheet body and are pointed out in detail within the next section.

Within the research work of Juechter et al. [29] a significant influence of the sheet thickness on the selective electron beam melting of functional elements has been discovered. To summarize the work it can be pointed out that varying sheet thicknesses have a significant effect on the porosity of the additive element and the resulting mechanical characteristics of the final part. The authors expect different heat transferring and storing capacities of the sheet with varying thickness as one of the possible reasons for varying solidification times and resulting porosities within the process. As this effect is also expected for laser beam melting, it is fundamental to understand and predict the distribution of sheet thickness during forming operation. Furthermore, residual stresses induced by forming operations have a significant influence on the following additive manufacturing step. Due to thermal energy induced during the generative manufacturing step residual stresses, which are stored within the semi-finished sheet, can be released and lead to shape deviation. This fact has not been researched adequately but is well known from heat treatment operations. Resulting shape deviation can then cause problems within the additive manufacturing process. Last but not least deviation regarding final part geometry can result into difficulties for the combined process chain. For example non-flatness of surfaces which are functional for additive manufacturing can cause process breakdown because of recoating failure within these areas.

To overcome these challenges, the superplastic forming operation is investigated. As an established manufacturing technique to produce parts with high shape accuracy, free from residual stresses and defined sheet thickness distribution, it is ideal to be used within this hybrid process chain. To understand the forming process as well as predict and control the final part, a preliminary numerical investigation is essential. Therefore, within this work a FE-model is set up to support the tool development by determining pressure, temperature and time for the superplastic forming process. This data will then be used to design a tool for experimental investigation and validation. Further it is the aim to numerically predict final part characteristics such as thickness distribution and final part geometry. This information will then be used to produce formed sheet metal parts adjusted to the following additive manufacturing step.

5 NUMERICAL MODEL

The numerical simulation was developed using the commercial finite element code LS-DYNA. Blank and die were modelled as shell elements and meshed with an element size of 1.0 mm. For the blank with an initial thickness of 1.5 mm, Belytschko-Tsay elements were chosen to ensure evolution of sheet thickness. In order to save time, only a quarter of the symmetrical model has been calculated. The setup of blank and die is illustrated in Figure 2.

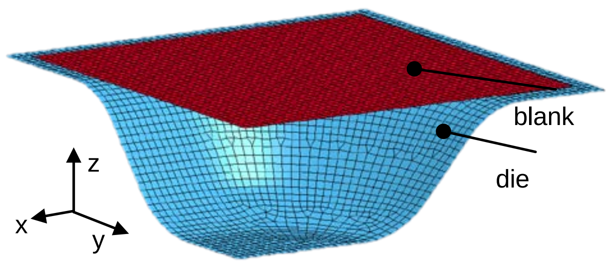

Figure 2 - Setup for simulating superplastic forming simulation in LS-DYNA

The die was considered as rigid body *(*020 RIGID*). To simulate the superplastic behaviour of the blank, the constitutive material model **064 MAT RATE SENSITIVE POWER LAW PLASTICITY* was employed which is suitable for strain rate sensitive material behaviour. Since superplastic deformation is dominated by large plastic deformation, elastic deformation was neglected. Additionally, strain hardening was considered to be very low and thus set to $n = 0$ [31]. Preliminary tensile tests were carried out in order to identify the strain rate sensitivity index m and the constant K. These results are shown in Table 1. An optimum strain rate was defined as 0.0002 s^{-1}, which has also been reported by Gillo [32] as ideal for superplastic forming of Ti-6Al-4V. All input values for the material model are summarized in Table 1.

Input parameters 064-RATE SENSITIVE POWERLAW PLASTICITY	
ρ (g/cm³)	4.48
Young's Modulus (N/mm²)	64000
v	0.33
K (MPa·s)	463
m	0.47
n	0
$\dot{\varepsilon}_{op}$ (s^{-1})	0.0002

Table 1 - Input parameters for modelling superplastic behavior in LS-DYNA

As contact condition, **CONSTRAINT NODES TO SURFACE* was chosen, which is recommended for superplastic forming operations by LS-DYNA [33]. Furthermore, die and blank were set as master and slave, respectively and the coefficient of friction was set to 0.2, which was also reported in literature [32]. Gas pressure was applied by using the function *LOAD_SEGMENT* and the pressure amplitude was regulated by using *LOAD_SUPERPLASTIC_FORMING* where a given function of time representing the pressure load is scaled in a range limited by two factors Sc_{min} (10^{-5}) and Sc_{max} (10^{4}) in order to maintain a constant strain rate. Additionally, mass scaling was applied to ensure calculation in a reasonable amount of time [34].

6 RESULTS OF THE NUMERICAL INVESTIGATION

The geometrical shape of the sheet after superplastic forming operation is shown in Figure 3. After 12800 seconds, the forming operation is completed and 100% of the blank is in contact with the die. Therefore, a maximum pressure of 35 MPa is predicted to be needed and sufficient to fully form the part.

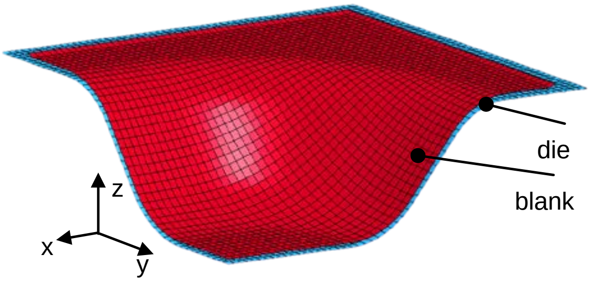

Figure 3 - Blank and die after superplastic forming operation

The qualitative estimation of sheet thickness distribution is presented as thickness reduction in per cent in Figure 4. In the initial stage of deformation, the sheet has no contact to the die and deformation is concentrated at the pole of the dome. Therefore, greatest strain occurs in this region at this stage and consequently most thinning of the part is located here. When the pole comes into contact with the die, the material gets locked against the tool by means of friction which prevents further deformation. The remaining regions continue to deform until they get in contact with the die, too. Since the corner of the die is the last to be filled, the greatest strain occurs there and thus thinning occurs here with a thickness reduction of a about 33%. As a result, these regions are most prone to failure [31].

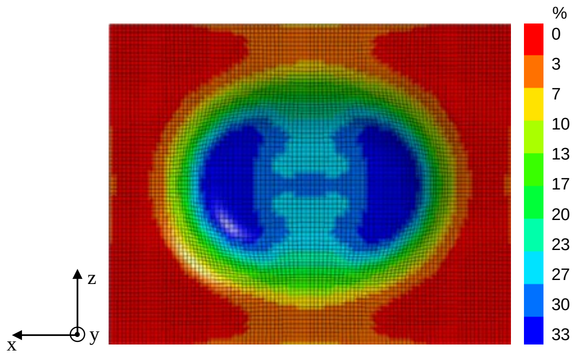

Figure 4 - Resulting thickness distribution from LS-DYNA after superplastic forming simulation

The pressure curve, illustrated in Figure 5, shows a similar progress compared to the work of Samekto and Roll [31] and can be divided into two stages – before and after contact of the sheet to the die. In the first stage, the pressure reaches a saturation value of about 6 MPa. In the second stage, pressure gets increased sharply with rising contact and ends up with a maximum value of 36 MPa.

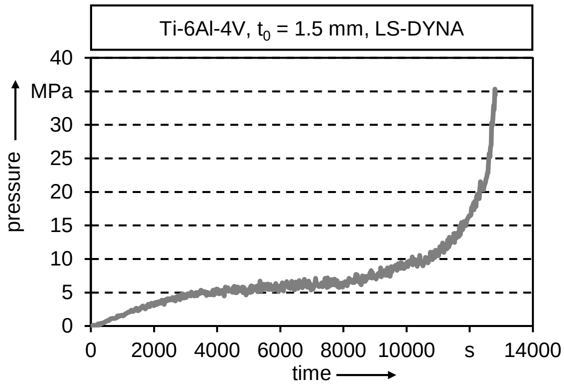

Figure 5 - Resulting pressure curve from LS-DYNA during superplastic forming simulation

Using the results of the numerical simulation, such as the presented pressure curve, it is possible to develop a tool concept which enables superplastic forming of Ti-6Al-4V cups at 925 °C at a maximum pressure of 36 MPa.

7 TOOL DEVELOPMENT ON THE BASIS OF THE NUMERICAL INVESTIGATION

Based on the results presented within the previous chapter a tool for superplastic forming of Ti-6Al-4V is developed and manufactured. This tool will further be used to build semi-finished sheet metal parts, which function as body parts for the combined process chain. First of all the shaping design of the tool is chosen as a cup in a way that the bottom is characterized by high flatness and sufficient geometrical 2D size for a wide range of LBM functional elements. Based on previous research [33] the geometrical dimension is chosen with an area of about 700 mm^2. A draft of the resulting tool concept is presented in Figure 6 where the bottom length is 40 mm and the width maximum is 20 mm.

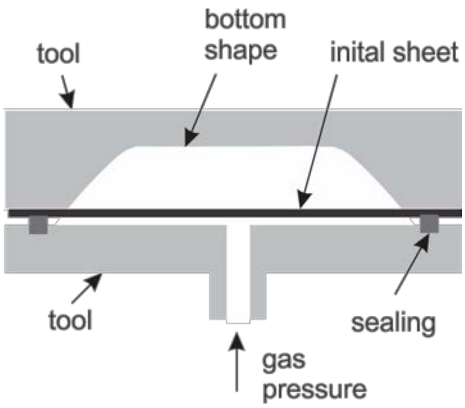

Figure 6 - Draft of superplastic tool concept

The three main challenges for tool development are temperature, pressure and flatness of the bottom of the final part, where the LBM-process takes place. To enable forming at a temperature of 925 °C the high temperature austenitic steel 1.4841 is chosen. Due to high percentage of Cr and Ni, this alloy is corrosion resistant up to temperatures of 1100 °C and further characterized by good mechanical properties. To induce pressure a pneumatic concept is chosen, using Argon gas. Considering the high reactivity of Ti-6Al-4V with air, Argon also functions as protective gas. Furthermore, a furnace Type LINN High Therm, KS-240-S is utilized which enables to reach 925°C as well as using Argon as inert gas during forming process. Due to the numerically predicted period of 12800 s for manufacturing, Argon is essential for forming as well as for protective gas to prevent oxidation of Ti-6Al-4V. Taking into account that 36 MPa gas pressure at a temperature of 925 °C is required to achieve final parts, the sealing between part and tool is manufactured out of Inconel 718. For the design of the sealing a C-shaped sheet covering a spring is utilized. In order to achieve high flatness the accuracy of the tool bottom is built with a flatness tolerance of 0.01.

The resulting parts built by superplastic forming are characterised by high shape accuracy and reduced residual stresses. Cups built by this process are ideal to by utilized as semi-finished parts for additive manufacturing.

8 SUMMARY AND OUTLOOK

Within the presented research work a new and innovative process chain combining sheet metal forming and additive manufacturing has been presented. First of all, the state of the art for the combination of metal body parts with generative manufacturing techniques has been pointed out. It was shown that only few research work has been carried out dealing with laser and electron beam melting on sheet metal. This investigation focuses on the challenge of producing semi-finished sheet body parts with high shape accuracy and low residual stresses for LBM. Within this context, superplastic forming is investigated as a manufacturing technology which allows the production of geometrically highly accurate parts, preventing springback and residual stresses. To estimate process parameters required for tool design, a numerical simulation of superplastic forming of Ti-6Al-4V sheet is set up. As results the requirements of the manufacturing process and the tooling system like maximum pressure and time are determined. Further a tool is designed taking into account process specific requirements. This superplastic forming tool will be used to validate the FE-Simulation as well as to produce sheet metal parts adjusted to the subsequent additive manufacturing step.

9 ACKNOWLEDGMENT

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as the Erlangen Graduate School in Advanced Optical Technologies (SAOT).

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Rotational Molding of Fiber Reinforced Plastics with Elastic Composite Core

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Abstract
The rotational molding with an elastic composite core is an interesting process for the manufacturing of fiber reinforced plastics (FRP) with polygon cross-section. The polygon shape can be used for an in-mould-assembly of FRP and metal structures. On this way a load transmission with combined form-fit and adhesive bonding can be realized. Those hybrid parts are a suitable lightweight solution for shafts, pipes and profiles.
The processing via rotational molding with composite core can be carried out as follows: First dry continuous fiber structures and the elastic composite core are assembled and then laid in a closed mold. Subsequently, liquid thermosetting resin is cast and the mold is rotated at high speed. During rotation the composite cores expands and pushes the matrix into the areas that normally, without the composite core, would not be impregnated. The rotation is continued until the fiber structure is fully impregnated and the polymer is cured.
Within this paper, the manufacturing of polygon profiles with an elastic composite core is described. An analytic approach is introduced, which enables an ideal design and material choice of the elastic composite core and the achievement of high fiber volume fractions for fiber reinforced plastic hollow structures. Furthermore the manufacturing of elastic cores are depicted.

Keywords
Fiber reinforced plastics, rotational molding, composites

1 INTRODUCTION

In drive technology, lightweight shafts and pipes are used to reduce rotating masses. This way, the entire drive system can be built with less power saving energy and resources.

Lightweight shafts are frequently produced with the so-called hybrid construction method. In these cases tribologically highly stressed parts such as gear wheels or bearings are made of metallic material, especially steel, whereas the areas for load transmission (over longer distances) are made of fiber reinforced plastics (FRP).

In this context, the connection between both materials is a key challenge, which has already been analyzed by many authors:

For example, Hufenbach investigated different form-fit joints for torque [1] and axial force transmission [2], Khalid et al. [3] and Mutasher et al. [4] reinforced metal pipes by wet filament winding. Esmaael and Taheri [5] investigated adhesively bonded joints, interference fit joints were examined by Lee and Lee [6] regarding finite-element simulation.

This publication presents the rotational molding (or centrifugal process) for producing polygon profiles and shafts made of FRP. The process has multiple stages: First, a dry fiber preform is pulled onto an elastic composite core. Subsequently, both components are put into a mold together with a defined amount of liquid resin. This mold is forced into rotation. With sufficient high rotational speeds and the centrifugal forces resulting from it, the impregnation process starts. The centrifugation process is continued until the fiber structure is fully impregnated and the resin is cured. With this process, hybrid shafts and profiles with a great weight-saving potential can be produced.

Within this publication, the state of the art of rotational molding (see Section 2), the functioning of the elastic composite core (see Section 3) and its production (Section 4) will be described in more detail. This publication ends with a short conclusion.

2 STATE OF THE ART: ROTATIONAL MOLDING

The rotational molding for producing hollow fiber reinforced plastics is a multistage manufacturing process.

First of all, a hollow preform is produced, e.g. by filament winding, tape winding (of woven fabrics or non-crimp fabrics) or by using braiding technology. An important requirement is that the formed preform shows sufficient stiffness. If this inherent rigidity is not given, there is the risk that the preform collapses when inserted into the mold or at the beginning of centrifugation. [7]

After that, a defined quantity of thermosetting resin is given into the mold. The resin is directly inserted into the mold before closing and clamping it into the machine or via a feeding arm during centrifugation, depending on the structure and equipment of the (turning) machine and the mold. The amount of resin m_m can be calculated with formula (1) as follows [7]:

$$m_m = \rho_m V_m = \rho_m (1 - \varphi_f) V \qquad (1)$$

The quantity m_m depends on the density of the matrix ρ_m, the fiber volume content of the FRP tube φ_f and the volume V of the tube.

In the next step, the mold is rotated. The arising centrifugal force must be higher than the weight force. Figure 1 illustrates these facts:

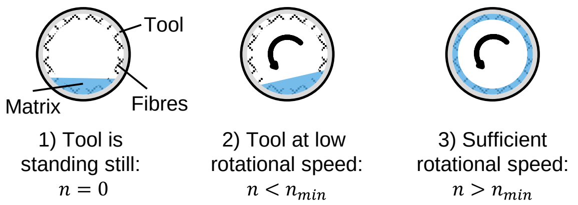

Figure 1 – Basics of rotational molding.

In accordance with this condition, a minimum speed n_{min} is required, which can be calculated according to formula (2) and depends on the gravity g and the radius of the FRP tube r [8]:

$$n > n_{min} = \frac{1}{2\pi} \cdot \sqrt{\frac{g}{r}} \qquad (2)$$

As soon as the minimum speed is reached, the impregnation of the fiber structure starts (see Figure 1, 3). The rotation is continued until the process of impregnation and curing is completed. This process can be accelerated by additional temperature control of the resin and the mold so that cycle times of just a few minutes are possible. However, rotation frequently occurs at a multiple of the minimum speed in order to obtain high laminate quality (high fiber volume content and minor air void content) [8].

3 OBJECTIVE: ROTATIONAL MOLDING WITH COMPOSITE CORE

3.1 Objective

The objective of rotational molding with an elastic composite core is to produce hollow structures of FRP with a polygon cross section. The polygon contour can then be used for load transmission onto metallic structures, which was already shown by [1]. This kind of hybrid structure is illustrated in Figure 2.

Figure 2 – Hybrid shaft with square FRP tube and metallic fitting.

However, the conventional centrifugation (without a core) is not able to create these kinds of structures. Due to the centrifugal forces, the resin is arranging itself inside the mold in the areas with the highest distance to the axis of rotation. That is why, for example, with a square cross section, resin-rich places would occur in the edges and dry areas in the middle between the edges of the tube. This behavior is shown in [7] and can be avoided by using elastic cores during the rotational molding.

The basic principle of rotational molding with an elastic composite core will be described in the following sub-section 3.2.

3.2 Basic principle

In rotational molding with an elastic composite core, an elastic and highly dense core is added during rotation. This core expands during rotation and pushes the resin into the areas which will not be impregnated normally. Figure 3 demonstrates the sequences of the process: First, the preform (1) and the core are inserted (2). Then, the required quantity of resin according to formula 1 is cast (3), the mold is closed and forced to rotate at a speed above minimum (4).

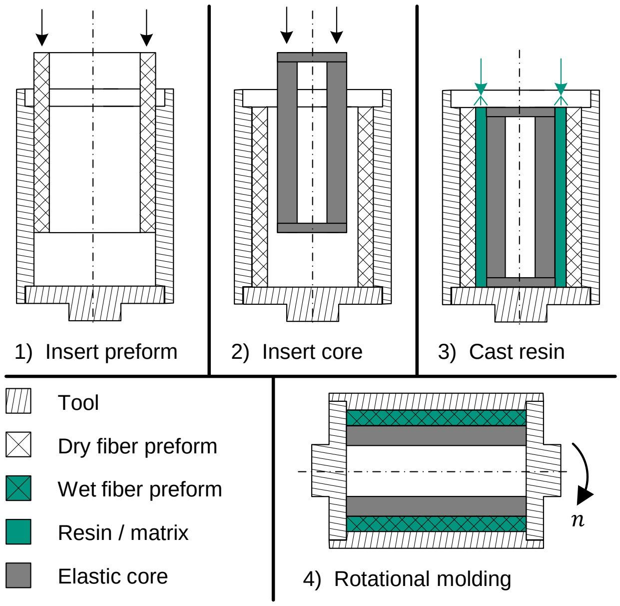

Figure 3 – Rotational molding with core (scheme).

The expanding core exerts pressure on the resin during impregnation. The pressure-elongation behavior of the core can be analytically calculated. The main features of this calculation model will be presented in section 3.3.

3.3 Analytic Model

The elastic elongation and pressure behavior of the core under rotation can be described by the following model. As shown in Figure 4, a hollow cylinder with the inner radius of the core $R_{c,i}$ and the outer radius $R_{c,o}$ is assumed. This cylindric core has a Young's modulus E_c, a Poisson's ratio ν_c and the density ρ_c.

In order to offer enough space between the elastic core and the textile preform for the imbedding matrix, the following condition (formula 3) for the outer radius $R_{c,o}$ has to be fulfilled

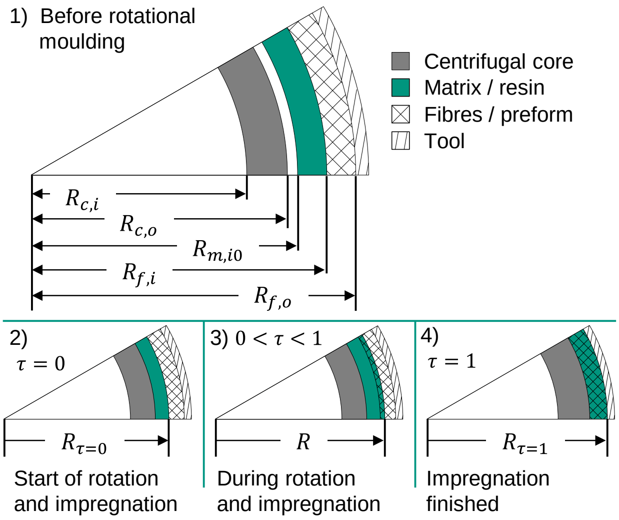

Figure 4 – Pressure and impregnation model for a cylindrical tube rotationally molded with a core.

$$R_{c,o} \leq R_{m,i0} = \sqrt{(1-\varphi_f)({R_{f,i}}^2 - {R_{f,o}}^2) + {R_{f,i}}^2} \quad (3)$$

The dimensions and characteristics of the preform, i.e. the inner radius of the FRP tube $R_{f,i}$, the outer radius of the FRP tube $R_{f,o}$ and the fiber volume content φ_f have to be taken into consideration.

The coupling of the Lamé-Navier equation with the deformation tensor and the generalized Hooke's Law leads for the shown model (see Figure 4) to the following expression for the pressure Δp_c, which is caused by the elastic core during centrifugation with an angle speed of $\omega = n/(2\pi)$:

$$\Delta p_c = A \cdot \left(\frac{\rho_c \omega^2}{4} \left(2{R_{c,o}}^3{v_c}^2 + 2R_{c,o}{R_{c,i}}^2{v_c}^2 + {R_{c,o}}^3 v_c - R_{c,o}{R_{c,i}}^2 v_c - {R_{c,o}}^3 - 3R_{c,o}{R_{c,i}}^2\right) + E_c\left(\sqrt{(1-\varphi_f)(R^2 - {R_{f,o}}^2) + {R_{f,i}}^2} - R_{c,o}\right)\right) \quad (4)$$

with

$$A = \frac{({R_{c,o}}^2 - {R_{c,i}}^2)}{(2{R_{c,o}}^2 v^2 + {R_{c,o}}^2 v - {R_{c,i}}^2 v - {R_{c,o}}^2 - {R_{c,i}}^2)R_{c,o}} \quad (5)$$

A detailed description of the assumptions and calculations leading to this expression, can be found in [7]. Here, R represents the position of the matrix front which may be depicted with the dimensionless impregnation progress τ :

$$\tau = \frac{R - R_{f,i}}{R_{f,o} - R_{f,i}} \quad (6)$$

In order to guarantee a functioning centrifugation process with a core, pressure Δp_c must always remain positive. This requirement can only be fulfilled by dimensioning the core's material and geometrical properties.

A highly elastic and at the same time extremely dense material is required for meeting the material properties. These characteristics may be obtained with a composite material possessing an elastic matrix and a filler of high density. When selecting the material, the possible application of the Mullins' effect [9] should be kept in mind in order to meet the required elastic properties of the composite material. For example, silicone rubber Elastosil® M 4511 ($E = 0.22\,MPa$ [7], $\rho = 1.22\,g/cm^3$ [10]) may be composed with lead shot ($\rho = 11.35\,g/cm^3$ [11]), gaining overall weight (filler volume content $\varphi_{fil} = 51.2\%$) [7].

The core's geometric design must also strive for a sufficiently high pressure. Consequently, the outer contour should lay as close as possible to the threshold value of formula (3). Subsequently, the core's flexibility needs to be adjusted by an hollow construction design. For a cylindrical core, the core's inner radius $R_{c,i}$ must therefore be dimensioned. For convenience of presentation, the normalized wall thickness of the outer radius $R_{c,o}$ of the centrifugation core t_c^* is introduced:

$$t_c^* = \frac{R_{c,o} - R_{c,i}}{R_{c,o}} \quad (7)$$

Figure 5 shows the influence of t_c^* on the centrifugation core's pressure Δp_c for the configuration mentioned above (with $R_{c,o} = 16.1\,mm$; $R_{f,i} = 17.5\,mm$; $R_{f,o} = 20.0\,mm$). It can be seen that there is a wall thickness $t_{c,opt}^*$ which maximizes the pressure component of the centrifugation core. The stiffness of the core increases with thicker walls which causes the pressure to decrease. Thinner walls lead to a lower mass of the core and thus, due to lower centrifugal forces, also to reduced pressures.

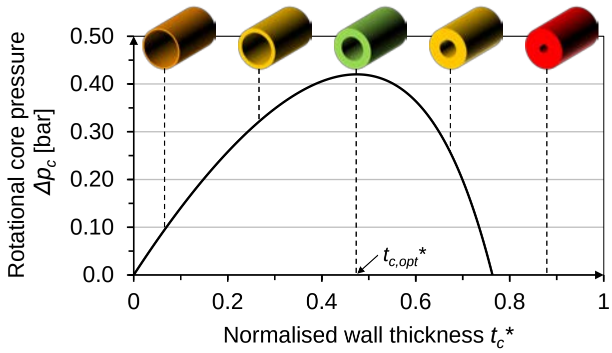

Figure 5 – Influence of normalised wall thickness $\boldsymbol{t_c}^*$ on pressure $\boldsymbol{\Delta p_c}$ at finished impregnation ($\boldsymbol{\tau = 1}$).

In the following, the dimensioning index M shall be introduced for the elastic core as well as the normalized pressure $\Delta p_c°$ after completed impregnation ($\tau = 1$) in order to obtain a universally applicable dimensioning of the core for any cylindrical geometries and materials:

$$M = \frac{E_c}{\rho_c \cdot {R_{c,o}}^2} \quad (8)$$

and

$$\Delta p_c^\circ = \frac{\Delta p_c}{\rho_c \cdot R_{c,o}^2} = A^\circ \left(\frac{\omega^2}{4} (2{\nu_c}^2 + 2(1 - {t_c}^*)^2 {\nu_c}^2 + \nu_c - (1 - {t_c}^*)^2 \nu_c - 1 - 3(1 - {t_c}^*)^2) - M\left(\sqrt{\varphi_f} R_{f,i}^* - 1\right) \right) \quad (9)$$

with

$$A^\circ = \frac{t^*}{2\nu^2 + t^*(\nu+1) - 2} \quad (10)$$

and the normalized inner radius of the FRP pipe.

$$R_{f,i}{}^* = \frac{R_{f,i}}{R_{c,o}} \quad (11)$$

Basic material	**Stainless steel**	**Lead**	**Elastosil® M 4511**	**Elastosil® M 4601**
E $[MPa]$	-	-	0.22	0.45
ρ $[g/cm^3]$	7.85	11.35	1.22 [10]	1.13 [13]
Composite $\varphi_{fil} = 51.2\%$	**Stainless steel + M4511**	**Lead + Elastosil® M4511**	**Stainless steel + M4601**	**Lead + Elastosil® M4601**
E $[MPa]$	0.108	0.108	0.221	0.221
ρ $[g/cm^3]$	4.60	6.39	4.56	6.34
M $[MPa \cdot m/kg]$	90325	65079	186544	134042

Table 1 – ***M*** values for different combinations of matrix and filling material.

Formula (9) and (10) show that high pressure and thus, the optimum process, is achieved, if the dimensioning index M is as small as possible.

Table 1 portrays different M values for four exemplary combinations of core filler and core

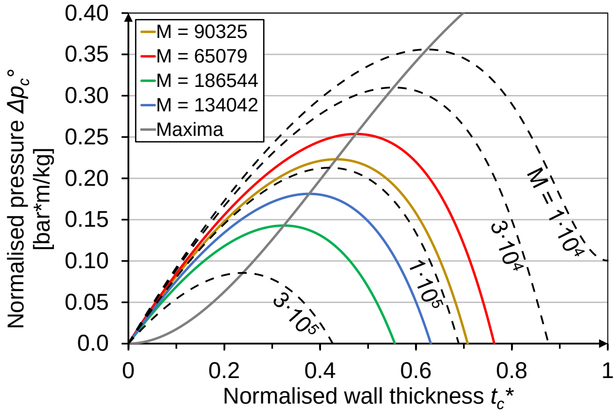

Figure 6 – Influence of different ***M*** values on the $\Delta \boldsymbol{p_c}^\circ$-$\boldsymbol{t_c}^*$-curve at 3000 rpm.

matrix. The composite properties are calculated by the rule of mixture [12] under the assumption that the filler does not contribute to the elastic deformation (at minor deformations) because of the Mullins' effect.

In the case M varies, the $\Delta p_c{}^\circ$-$t_c{}^*$-curve moves along a Sigmoid function (see Figure 6). Smaller values of M result in a higher $\Delta p_c{}^\circ$. In the case of smaller M parameters, the ideal wall thickness $t_{c,opt}{}^*$ also shifts to higher values.

Thus, the ideal wall thickness $t_{c,opt}{}^*$ can be determined for given boundary conditions regarding material, technology and geometry in order to reach the maximum pressure $\Delta p_c{}^\circ$. It can be achieved by differentiating formula 12 with the following criteria:

$$\frac{\partial \Delta p_c{}^\circ}{\partial t_c{}^*} = 0 \text{ and } \frac{\partial^2 \Delta p_c{}^\circ}{\partial {t_c{}^*}^2} < 0 \quad (12)$$

Consequently, a diagram according to Figure 7 can be created for some discrete rotational speeds which can be referred to for dimensioning the core together with formula 8.

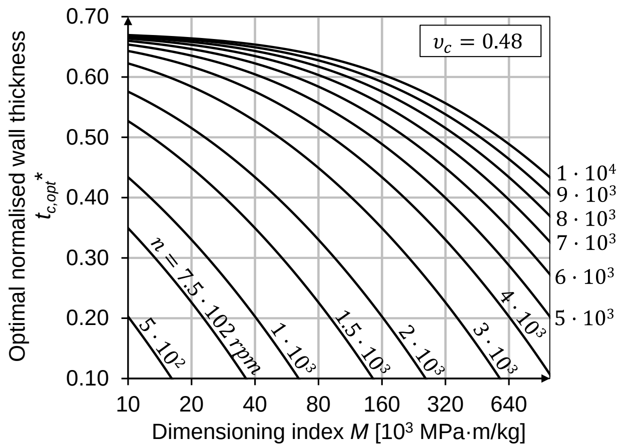

Figure 7 – Dimensioning diagramm - $\boldsymbol{t_{c,opt}}^*$ as a function of ***M*** for different rotational speeds.

For the material and geometry combinations from Figure 5 and Table 1 with $M = 65079\, MPa \cdot m/kg$ and $n = 3000\, rpm$, an optimum normalized wall thickness $t_{c,opt}{}^* \cong 0.47$ can be read off. The upper threshold value of the normalized ideal wall thickness $t_{c,opt}{}^*$ is limited by the Poisson's ratio v_c.

4 MANUFACTURING OF ELASTIC COMPOSITE CORE

4.1 Manufacturing sequence

Section 3 has presented the theoretical requirements for a functioning centrifugation process with a core. The core should thus consist of a composite material with an elastic silicone rubber as matrix and lead balls as highly dense fillet.

Such a core may be manufactured in a casting process. In the case of two-component systems of the silicone rubber, the filler should firstly be mixed with component A. Subsequently, component B is added to initiate vulcanization. This results in a potential core with equal filling particle distribution. Some particles are located openly at the surface. An example can be seen in Figure 8.

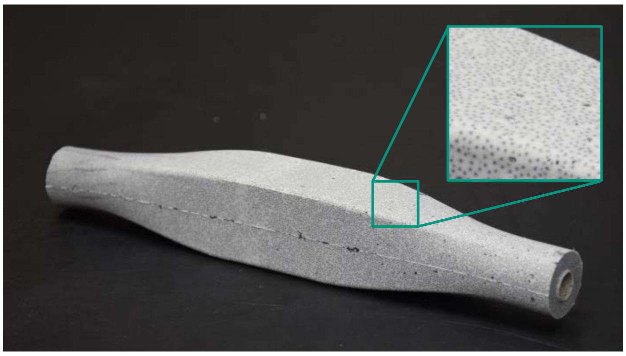

Figure 8 – Example of a composite core consisting of silicone rubber and lead particles

Such a construction where some particles are located openly at the surface, however, reduces the reusability of the core - when it comes to manufacturing further components - by approximately 2-5 cycles. The reason for the reduced reusability is found in the Mullins' effect [9] and the expansion of the core during the centrifugation process. During expansion, pores may emerge at the surface between the particles and the matrix. Cracks easily arise at these pores. In the case of further crack development, the core might be damaged until its loss of function.

The core may more often be reused if protective layers are applied to its surface. Furthermore, protective layers shall be applied to the ends of the hollow composite core to seal the core completely

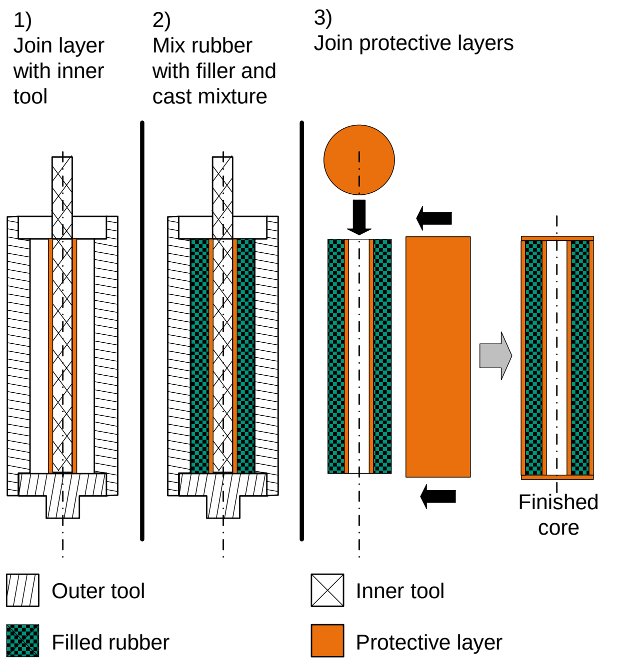

Figure 9 – Manufacturing sequence of core with protective layers for the rotational molding with core.

and to impede the matrix from flowing into the core's insides.

The manufacturing of cores for the rotational molding with protective layers (which is made of the same elastomeric material as the core) is illustrated in Figure 9.

In the first step of the production, an internal protective layer is rolled onto the internal tool shaft (see Figure 9, 1) and subsequently both are joined with the outer form-giving tool. Then, a mixture of a pourable, elastomeric matrix is blended with a filler and poured into the mold at ambient pressure (Figure 9, 2). A filling volume of approximately 51.2 % is reached if the mixture of silicone rubber Elastosil® M4511 and lead particles (particle size: 0.6 – 1.5 mm) is poured at ambient pressure.

A hollow basic core with an inner protective layer develops after complete curing. The outside and the lateral surfaces of the core are adhesively bonded with further protective layers in the final step. All protective layers may also be produced in a casting process.

4.2 Influence on composite core design

The protective layers influence the flexibility behavior of the entire core since the protective layer locally represents a pure elastomeric matrix material. In addition, less core mass is available at the same overall wall thickness which may contribute to reach high centrifugal forces. Thus, the ideal balance between the increased protective effect (higher wall thickness of the protective layer) and sufficient flexibility for the high centrifugal pressure needs to be found (thinner wall thickness).

The influence of the inner and outer protective layer around the core can be calculated with the appropriate transition boundary conditions for the differential equation system of Lamé-Navier equations with three areas. At the transitions, the same tensions and shifts are assumed. They are derived as described in [7] or respectively pursuant to formula 4.

Thus, the influence of the protective layer thickness may be depicted for the presented configuration according to Figure 5 by exerting pressure Δp_c via the normalized wall thickness t^* (see Figure 10). In this context, the core's external radius $R_{c,o}$ is kept constant.

Figure 10 demonstrates that a significant reduction occurs starting with a thickness of the protective layer of 0.5 mm. This reduction can be explained by the lower composite material volume and the corresponding decrease of the centrifugal inertia forces as well as the increased stiffness of the protective layer which is due to the elastic composite behavior and the missing Mullins effect in this area. Consequently, the ideal thickness of the protective layer is around 0.2 to 0.4 mm for the

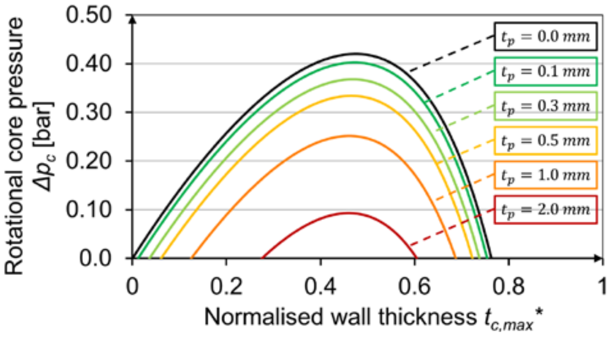

Figure 10 – Influence of protective layer thickness on core pressure

examined loading condition (presumably also for most other conditions).

5 CONCLUSIONS

The rotational molding with elastic core is an innovative approach for the manufacturing of hollow FRP shafts and pipes. The elastic core is enabling high volume fraction and polygon cross sections. The introduced index M and the dimensioning diagram simplifiy the design and material choice of the elastic core.

6 ACKNOWLEDGMENTS

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8 BIOGRAPHY

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Mechanical Characterization of Coir Epoxy Composites and Effect of Processing Methods on Mechanical Properties

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Abstract

Composite materials have now attracted wide acceptance in product development and manufacture especially in automotive and aerospace applications where weight reduction and low fuel consumption are critical product performance metrics. In most applications, glass and carbon fibre composites are used. However, natural fibre composites also offer attractive properties. They are competitive especially in terms of price and density when compared to glass and carbon fibre composites while providing similar mechanical properties. Commonly available natural fibres include coir and sisal. Resin transfer moulding (RTM) process is also an established technique for manufacturing composites as it offers good surface finish and dimensional control. The aim of this paper is to investigate the effect of resin transfer rate on the performance of the product. Coir fibre / epoxy resin composites are prepared using RTM for differing resin transfer rates and fibre fraction for treated and untreated fibres. The results obtained indicate a slight reduction in performance with reduction in resin transfer rate. However, stiffness remained unaffected. Improvement in stiffness and strength with increasing volume fraction was reported which was in agreement with literature. However, the data exhibited an optimum fibre volume fraction of 30% beyond which performance deteriorated. This investigation indicates that further work is required to optimise the production of natural fibre composites using RTM.

Keywords

Coir epoxy composites, Mechanical performance, Natural fibres, Resin transfer moulding

1 INTRODUCTION

When a material contains more than one phase that is artificially blended together, it is then considered to be a composite material. Most commercial composites are made by using fibers to reinforce a matrix. The matrix can have fillers added to modify behavior such as improving fracture toughness [1]. A typical example of a commonly used composite is carbon fiber composite in which carbon fibers are used to reinforce a polymeric matrix, typically epoxy resin. The fibers in the composite can be short or continuous, multidirectional or unidirectional, woven or non-woven. A matrix alone excluding fillers is three-dimensionally continuous (isotropic). This means that directional properties are the same in all directions. Once fillers have been implemented into the matrix they can either be continuous or non-continuous depending on the intentions of the designer [2].

Natural fiber composites are becoming more popular today than ever before. With the increase in environmental costs of producing synthetic fibers, natural fibres have now become a necessity. Furthermore, natural fibers are renewable and can also be extracted from freely growing plants [3]. The advantages of natural fibers are therefore being exploited more and more in automotive and aerospace fields. However, they have largely been restricted to non-critical applications such as interior panels. They are also being applied in other fields as well, as they provide ideal strength at almost 50% of the weight. The main advantages of natural fiber as compared to glass fiber composites include lower density, lower toxicity, lower cost and biodegradability [4]. Stiffness, impact strength, flexibility as well as modulus are other properties that are favorable amongst natural fibers [5].

However, there are slight drawbacks to the use of natural fibers as opposed to synthetic fibers. These include water absorption, low working temperatures and the poor compatibility between the synthetic polymers and the natural fibers [6].

There exist several manufacturing methods for processing composites. The hand laminating or hand lay-up (HL) is the cheapest option [7]. In this case fibers are hand laid in a mold and the resin is applied by hand typically using a hand brush. The main challenge with had lay-up is air entrapment which results is air bubbles and defects in the component. Vacuum bagging combines the hand lay-up together with vacuum bagging to reduce air entrapment. Unfortunately, dimensional control remains a challenge with these techniques. Resin transfer molding (RTM) uses vacuum injection for both molding and air removal leading to better dimensional control and less defects [8]. Pultrusion is a process where the resin granules are impregnated with the fibres and are pulled through a die. This is the most expensive technique and is therefore rarely used [9].

Given this background, there is need to assess the effectiveness of using the RTM method as a production technique for coir fiber–epoxy resin composite components. The hand lay-up and the RTM process offer the best option for low cost production. The aim of this investigation is to therefore two pronged: (1) to determine whether a coir epoxy composite is a suitable replacement material for synthetic fiber composites with specific focus on glass and carbon fiber composites which are currently being used in the University of Johannesburg solar car project and (2) to compare the effect of hand lay-up and RTM processes on the mechanical performance of the resulting components.

2 EXPERIMENTAL PROCEDURE

2.1 Aim

The aim of the experiments was to determine the mechanical properties of components produced using the hand lay-up and RTM processes for varying fiber fractions.

2.2 Materials

Coir fiber used in this investigation was supplied by the Coir Institute of South Africa. Coir fiber is 100% natural and originates in the outer husks of coconuts. It is part of the seedpod of the coconut palm. Ampreg 21, a two part clear epoxy resin that cures at room temperature was used as the matrix. This resin was supplied by AMT Composites. Ampreg 21 is a UV resistant clear liquid epoxy. It has a specific gravity of 1.09, Shore D hardness of 75, mixed viscosity of 100 cps, pot life of 45 minutes and has a curing time of 16 hours.

2.3 Pre-fabrication Preparations

2.3.1 *Specimen Geometry*

The experimental tests were conducted in accordance to ASTM 3039. The tensile test specimen selected was a flat plate specimen of dimensions 250 × 25 × 2.5 mm.

2.3.2 *Coir Fiber Treatment*

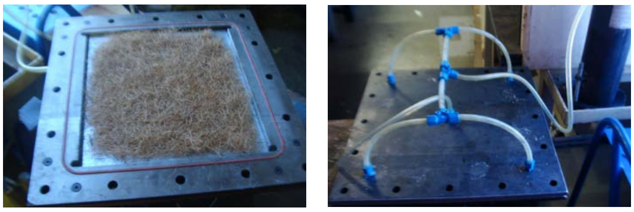
Fiber-matrix adhesion is key to the performance of a composite components. Special care was taken to prepare the fibers. After cleaning and cutting, the coir fibers were treated with a 2% solution of sodium sulphite and sonicated in an ultrasonic apparatus for approximately 2 hours. After the sonication the coir fibers were washed with deionized water and dried at room temperature for 2-3 days. This is called sulphite treatment. Once the treatment was complete the fabrication of the epoxy composite process began.

2.3.3 *Processing Techniques*

The two methods used for the fabrication of the epoxy composite were the Hand Lay-up (HL) and the Resin Transfer Molding (RTM) techniques.

2.3.4 *Resin Transfer Molding*

The first step before using the resin transfer mould is the coating of release agent. The coating method includes applying a single coat and letting it set for approximately 5 minutes before applying another coat and leaving it to set before use. The coir fiber was then placed into the mould. The fiber was measured to a specific mass to provide the right volume fraction in relation to the volume of the mould. Fiber volume fractions used were 4%, 6%, 8% and 10%. The fibers were fairly loose and so to produce an almost mat like feature, the fibers were randomly distributed and then compressed in the mold using weights. The setting up of the resin transfer mould was then carried out. However, prior to the run time, the resin and the hardener must be mixed to form the polymerized epoxy resin. The resin to hardener ratio used was standard AMT 100:38. Figure 1(a) shows the fiber in the mold and Figure 1(b) shows the RTM setup. The vacuum pressure was adjusted to vary the resin transfer rate.



(a) (b)

Figure 1 - RTM process configuration

2.3.5 *Hand Lay-up Technique*

The hand lay-up process was slightly simpler and less tedious than the RTM process. The fiber preparation followed the same approach used in the RTM process. Once the release agent was dry, the chopped fibers were placed in a container with required volume fraction. The resin to hardener ratio used for the hand lay-up process was 100:20. This was meant to increase curing time to improve handling due to the slower process. The mixture was then carefully laid in the mold which was then closed, locked with bolts and left to cure. The process is shown in Figure 2.

Figure 2 - Hand lay-up a)fibre distribution and b) resin distribution

Produced specimen were then cut into test specimen using band saw and polished using a grinder. Samples of the produced specimen are shown in Figure 3.

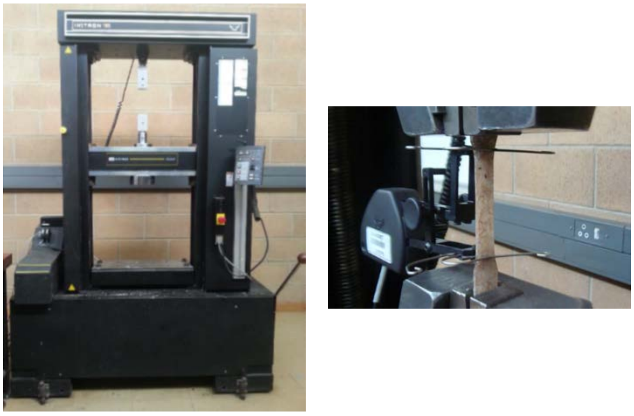
(a) (b)

Figure 3 - Specimen with different fiber volume fraction (a) 4% (b) 6%

2.4 Equipment

2.4.1 *Tensile testing*

Tensile tests were conducted on an Instron 1195 tensile testing machine controlled by Bluehill 2 software. This is a screw type machine which was used with a 100 kN load cell, see Figure 4(a). Figure 4(b) shows the mounting of the specimen in the testing machine grips showing extensometer mounting configuration.



(a) (b)

Figure 4 - Tensile testing set-up (a) Machine (b) Specimen mounting with extensometer

3 RESULTS

3.1 Fracture Analysis

Figure 5 shows the fractured specimens with 4 % fiber volume fraction. Fracture for three of the four specimens occured in the gauge section which is consistent with expectation. For one specimen fracture occurred outside the gauge section. This may been due to one or two reasons; either the jaws were not alighed and tightened properly or the sample was not cut to consistent ASTM dimensions due to human error as this was a manual process. However, specimens with 6% and 8% and 10% fiber volume fractions exhibited consistent fracture patterns.

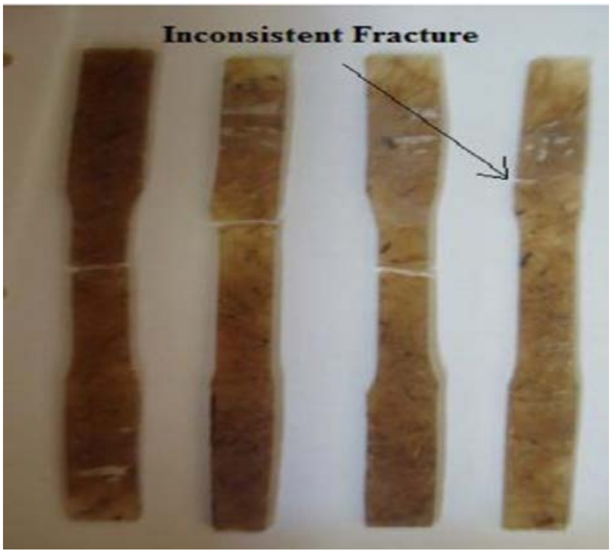
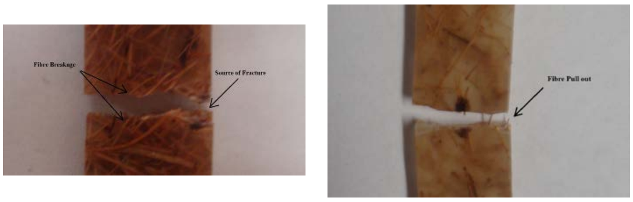


Figure 5 - Fractured specimens 4% vol

Almost all specimens indicated horizontal fracture. Horizontal fracture is an indication of brittle fracture. Brittle fracture is predominantly stress droven and the fracture direction is perpendicular to the direction of applied tensile stress. There was also no signs of plastic deformation by the naked eye and this further supports the brittle fracture observation. This is shown in Figure 6 (a).



(a) (b)

Figure 6 - Sample fractured specimens (a) Flat (b) Fiber pull out

Figure 6 (b) also shows fiber pull out observed in some of the specimens. Fiber pull out is an indication of poor adhesion between the matrix and the fibre while fiber breakage is an indication of good adhesion between matrix and fibre. Fibre pull out may be due to fibre length not meeting the critical fibre length requirement. Another possibility could be the effect of fiber orientation. The direction of the force is vertical whereas orientation is random. A fixed orientation provides a better adhesion between fibre and matrix and hence more predictable load carrying cappacity. Another factor that contributes to fracture is volume consistency of the matrix. Volume of the matrix can be altered due to voids and bubbles. These surface voids can be the source of fracture.

A sample of the close up of the fractured surface is shown in Figure 7 exhibiting the appearance of the fibre pull out feature.

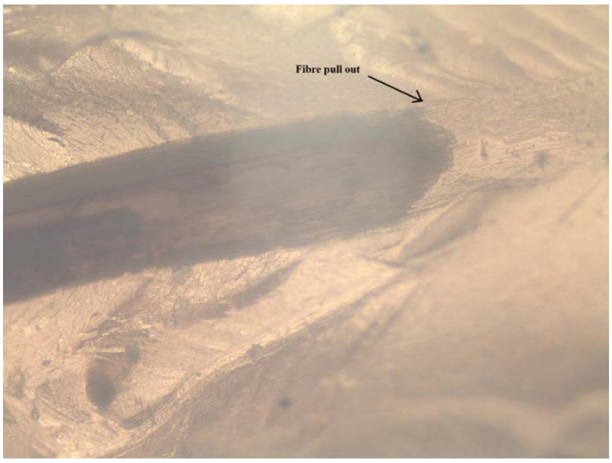


Figure 7 - Sample fractured specimen showing fiber pull out feature

3.2 Tensile Test Results

Figure 8 shows the typical stress strain response obtained for specimen with 8 % fiber volume fractions. The graphs are for four different specimens. The variance between the specimens acceptable. The stress strain response confirms the brittle fracture observed on the fractured specimens.

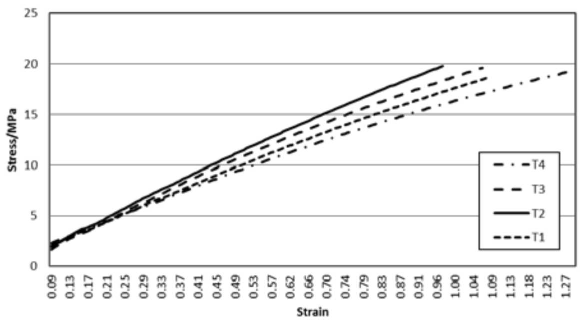


Figure 8 - Stress vs strain at 8 % fiber fraction

The effect of fiber fraction on composite mechanial properties for specimen produced using the RTM process is shown in Figure 9. It is clear that the volume fraction affects the mechanical properties of the composite. This is more pronounced for elastic modulus and less pronounced for tensile strength. The results seem to suggest the existence of an optimum volume fraction around 8%. This needs further work to confirm.

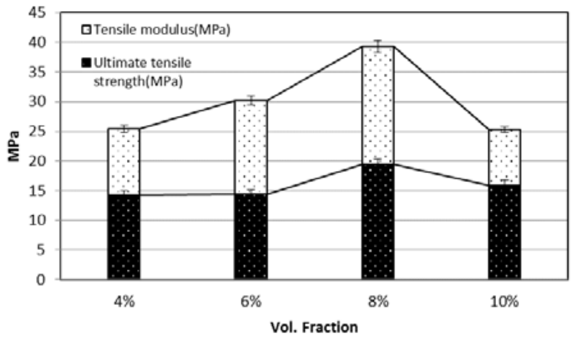


Figure 9 - Effect of fiber volume fraction on mechanical properties

A comparison of the mechanical properties for the high and low rate of resin transfer in the RTM specimens is presented in Figure 10. The results show better performance of the high rate (HR) of resin transfer compared with the low rate (LR) specimens. This is more pronounced for tensile strength and less so for elastic modulus. The average LR tensile strength was found to be 29.6 % lower than that for the HR process. Resin transfer rate therefore affects the mechanical performance of the composite.

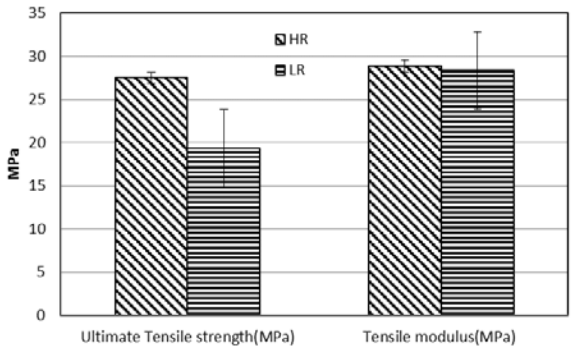


Figure 10 - Effect of resin transfer rate

3.3 Micro hardness

Micro hardness tests were conducted on all the specimens to determine the effect of loading on the softening of the specimen. Measurements were made for varying distance from the fracture surface. No consistent pattern was observed which shows that the loading did not have an effect on the hardness of the composite.

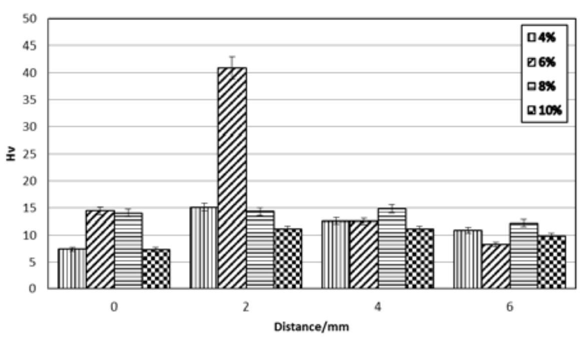


Figure 11 - Microhardness of fraction percentages

4 COMPARISON RTM AND HAND LAY-UP

On average the RTM process produced better performing specimens in terms of mechanical properties. The difference was more pronounced for tensile strength and less so for elastic modulus. This is summarized in Table 1 for the specimen with 4 % fiber volume fraction. However, the RTM process is more time consuming that the manual lay-up due to suction pressure adjustments required to achieve optimum resin flow rate. Moreover, mechanical properties are affected by the resin flow rate.

Extraction rate	**UTS (MPa)**	**Tensile modulus (MPa)**
RTM	28.61	31.25
MANUL	18.35	29.25

Table 1 - Comparison of RTM and hand lay-up for specimen with 4% fiber volume fraction

5 CONCLUSION

Coir fiber-epoxy resin composites were successfully made using the resin transfer molding (RTM) and the manual hand lay-up processes for varying fiber volume fraction. The specimen prepared were then characterized for mechanical performance. Based on the results obtained, the following conclusions can be made:

1. Coir fibers can be successfully used to strengthen epoxy resins to form a natural fiber composite
2. The strength of the composite produced is significantly dependent on the volume fraction of the fiber used
3. The RTM process produced specimen with superior mechanical performance compared to hand lay-up
4. The tensile strength of RTM specimen was about 29.6 % higher than that of hand lay-up and elastic modulus was not significantly affected
5. The RTM produced specimen whose quality is dependent on the rate of resin transfer that has to be determined by trial and error prior to making final components
6. RTM process is recommended due to its favorable geometrical control
7. Results seem to suggest the existence of an optimum fiber volume fraction of about 8% which produces maximum tensile strength

Further work is recommended to determine optimum resin transfer rate, the optimum fiber volume fraction and the optimum fiber diameter and length.

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7 BIOGRAPHY

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The Effectiveness of Different Types of Context-Adaptive Tutors During Quality Control in Carbon Fiber Reinforced Polymer Production

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Abstract

Even though carbon fiber reinforced polymers (CFRP) have outstanding mechanical benefits (low weight, high stability), the manufacturing process is fragile. Small variations in the process result in decreasing mechanical stability and additional production costs. This is especially critical for small lot sizes in which automation is not profitable. Instead, manual processes are required, which are highly prone to variances in process quality. As the quality control within the manual production is quite demanding, an assistance system is needed to guide workers and reduce the variance in product quality. Augmented Reality (AR) applications could be used to support workers during quality control. Yet, no empirical studies of the applicability of AR to support CFRP processing have been carried out. Therefore, we present an AR-based prototypic worker support system for CFRP manufacturing. Empirically, the influence of three different assistance modalities (auditory, visual, combined) and a control condition (no feedback) on quality control were investigated. In addition, the impact of workers' individual factors on performance was studied. Overall, the combined feedback worked best. Taking user factors and performance into account will provide useful guidelines for the development of a context-adaptive support system.

Keywords

Carbon Fiber Reinforced Polymers (CFRP), Augmented Reality (AR), Context-adaptive Worker Assistance, Human Factors

1 INTRODUCTION

Fiber reinforced plastics (FRP) are an essential material group for components that require light-weight structures with advanced mechanical properties, e.g., for aerospace and automotive applications [1]. Especially carbon fiber reinforced plastics (CFRP) are characterized by their excellent mechanical properties and light weight [2].

Not least through the increasing demand of the automotive sector (e.g., BMW i3), the production of CFRP components is close to mass production (> 100.000 parts per year). The challenges for CFRP in mass production are the relatively high material and manufacturing costs. The call for a significant reduction in manufacturing costs of high-tech CFRP components cannot be reached by the current automation approaches in production technology [3].

Especially in the aerospace industry with its small production batches, high complexity, and variety of product parts, a non-automated production implies considerable process dispersion and a high rework rate. Because of the deficiencies in appropriate manufacturing technologies, such as automated handling systems to control each textile layer during its placement, a fully automated confection machine for CFRP is not yet available [4]. Therefore, many manufacturing processes for CFRP still involve manual production steps that require an additional quality control system.

The build-up of the dry textile structure, called preform (Fig. 1), is an important part of this process chain, as it greatly affects the dimension, geometry, and the mechanical behavior of the final part.

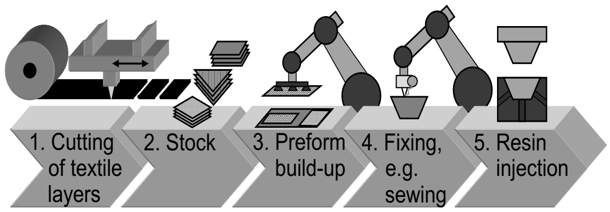

Figure 1 - Manufacturing of textile preforms

Only a reliable quality assurance system can ensure a feasible production of the required high-quality products. Especially the fiber orientation of each textile layer is a crucial process parameter to assure the mechanical properties during the construction of the preform. Such a system would industrialize the process (ready for serial production), enabling customers to profit from the advantages of this technology in manifold products [4].

With the fiber measurement system (FMS), a machine vision system for the critical inspection of the fiber orientation in textile CFRP structures has been applied. Because of the high costs for integrating the FMS in the inline process, the aim of this study is to improve the manual processes by supporting the workers with the FMS. Therefore, an AR-based prototypic worker support system for CFRP manufacturing was investigated.

2 FEEDBACK IN WORKER ASSISTANCE

In the following we briefly outline the state of the art with regard to two major aspects. One is the utility of AR for worker assistance. The second aspect regards the feedback modality to support workers during the quality control.

An overview of AR applications in manufacturing, current technologies for building AR applications, and their design is given in [5]. In contrast to virtual reality, in which users are completely immersed in the virtual environment, AR allows users to have the virtual objects superimposed to the real world [6]. AR applications for worker support have been demonstrated in assembly and maintenance in the automotive and aerospace industries [7]. In assembly tasks it could be shown that the performance using AR systems outperforms head-mounted displays as support systems. However, AR support shows also limitations: AR support increases assembly performance at the cost of increased fatigue and orientation problems [8].

Another basic question is the design and the appropriate modality of feedback. When information is presented visually, attention has to be divided between the visual control of the inspection task and the tutor information [9]. The concurrent processing of tasks that share common resources leads to performance losses [10]. Tutorial feedback may also be presented auditorily. Auditory information may be combined with the manual task more effectively, as they rely on different perceptual channels. However, auditory presentation of side information may also have detrimental effects on short term memory of workers, especially during longer working periods [11] [12]. The combination of visual and auditory feedback has been shown to be especially beneficial [13], leading to a better task performance and a higher learnability. Apparently, the information processing system profits from the double-coding, referred to as “redundancy gains” [14]. So far, sparse know-ledge is present with respect to utility of visual and auditory AR-supported feedback systems in carbon fiber manufacturing [15].

3 DESIGN AND IMPLEMENTATION OF A CFRP MANUFACTURING SUPPORT SYSTEM

First of all, we performed a careful and thorough definition of the requirements before the actual design and the implementation of a prototypic CFRP manufacturing support system was accomplished.

3.1 Requirements’ engineering

In order to understand the practical task requirements within every-day working processes, an interview study was carried out. CFRP workers (different experience and domain knowledge) stated hat an assistant system might be helpful, especially in the cloths alignment process. Based on this qualitative study, basic requirements for the support system in CFRP manufacturing were defined:

- The support system should be designed for stationary usage. Although the workers frequently changed positions and were standing at different locations around the mold, the main work area was around a single mold.
- Feedback should be accomplished with different modalities to meet the requirements of an increasingly diverse working population as well as unsteady working settings in which visual feedback can be used if the noise of a nearby machine drowns out the auditory feedback [16].
- Furthermore, we use dynamic feedback that visualizes the fixed target orientation and the current orientation which convergences to the target orientation as the user rotates the cloth.

3.2 System implementation

In a prototypic experimental setup, users are asked to create a stack of sheets with CFRP-like textures, in which the fiber orientations must follow a given pattern relative to the base orientation. This prototype of the planned support system was created in a short amount of time, to answer fundamental design issues quite early. In the ongoing design process, components and sub-processes that have been identified as important were modeled down to the desired level of detail [16]. Further, the concept of Virtual Testbeds provides an ideal basis for collaborative design [17]. For the orientation detection hand movements, a mock-up was developed using Microsoft’s Kinect sensors. The integrated skeletal tracking engine recognizes the user's body poses and returns up to 20 Cartesian joint positions of a human body [18]. The input variables of the system prototype are 3D-positions of the user’s hands, provided by the Kinect sensor at a frame rate of 30 Hz. These sensor data are subject to noise and jitter. Hence, a moving average low pass filter with six frames to smoothen the input was applied. The joining vector of the smoothed hand positions is then projected into a plane parallel to the ground in order to calculate the yaw-angle $\psi(t)$ of the horizontal hand positions, according to the following convention: $\psi = 0°$ corresponds with the initial position, both hands are parallel in front of the user’s body. If the user’s current sheet analog was a car’s steering wheel, the car would be going straight. Values for $\psi > 0°$ are used for clockwise movements (car analogy:

steering right), and $\psi < 0°$ for counter-clockwise movements, respectively. User guidelines ensure that this hand orientation satisfies $-180° < \psi(t) \leq 180°$ at all times. However, due to potential inaccuracies of the Kinect sensor's skeletal data output as well as too challenging alignment tasks, we further constrain valid hand orientations to a range of $-45° < \psi(t) \leq 45°$ via operator instructions. For further calculations, a coordinate system was considered in which $0°$ is pointing straight away from the user so that we have to transform $\psi(t)$ to $\psi'(t) = \psi(t) + 90°$. Due to the experimental setup, the true texture orientation of each sheet or layer is not $\psi'(t)$, but $\varphi(t) = \psi'(t) + \alpha_i$, i.e., shifted about an offset α_i with respect to the user's hand positions. This offset is individual to each layer and known to the system. As long as workers are using the sheets in their intended order, the current plate's orientation $\varphi(t)$ is known to the system at all times. The users are given tasks to place each layer with a certain angle offset β_i relative to the base layer γ, resulting in the target orientation φ_i^0. The assistant system's objective is then to help the user minimize the error $\delta_i(t) = \varphi(t) - \varphi_i^0$ and to increase the speed at which small values for $\delta_i(t)$ are reached.

3.3 Design of visual and auditory feedback

The visual assistant system is displayed on a 2D-screen, easily visible to the users. In empirical tests, we found that the absolute target orientation φ_i^0 is crucial information to the users while its calculation is confusing at the same time. Hence, a huge virtual sheet including its texture orientation is displayed, correctly aligned to the users. The current state $\varphi(t)$ is overlaid as transparent texture with a different color so users can constantly verify their progress.
As auditory feedback, we provide a signal similar to common parking assistance systems. The pulse frequency of tones with constant pitch varies according to the current situation. When the absolute angle error ($\epsilon = \mathrm{abs}(\delta_i(t))$ is below a certain threshold δ_0, the signal changes to a constant tone. During normal operation (for $\epsilon > \delta_0$), the tone is active for a time t_{on} and pauses for a duration of $t_{off} = c \cdot \epsilon$. We found $\delta_0 = 7°$, $t_{on} = 0.2s$, and $c = 6$ to work well in practice.

4 RESEARCH QUESTIONS

- Which feedback type leads to the most efficient and effective tutor system?
- Are individual user characteristics – spatial visualization ability and technical self-confidence – crucial for performance outcomes?

5 EXPERIMENTAL EVALUATION

5.1 Variables

As *independent variables* the within-factor "feedback-type" was examined in four steps: (1) auditory, (2) visual feedback, (3) a combination of auditory and visual feedback. In addition, (4) a control condition with no tutor was performed. As dependent variables, *efficiency*, measured by completion times (sec), and *effectiveness*, measured by the average degree of misalignment (δ_i at the end of each task) of the carbon fiber cloth of the stand-in sheets, which had to be positioned accurately, were quantified.

As individual user characteristics, the *spatial ability* and the technical self-efficacy were psychometrically assessed. Both factors have been found to impact performance in computer-based tasks [21] [22]. To measure *spatial ability*, participants completed a spatial visualization test [23]. Technical self-efficacy, the individual confidence in one's capability to use technical devices [24] was assessed using an 8-items questionnaire.

5.2 Participants

Overall, 41 participants volunteered to take part. In order to mirror the diversity of workers, participants had diverse experience and domain knowledge with the manufacturing of CFRP and the group showed a wide age (21-55 years of age, M = 27.85, SD=8.4). In order to get insights into the suitability of the settings, we decided to use young and technology-experienced adults (mostly students).

5.3 Task and procedure

To familiarize the participants with the task, first, a short tutorial was given, explaining the different possible types of feedback by turning their attention to the visual presentation in front of them on the wall and to the sound system. At the beginning of each trial, participants had to hold the sheet analog horizontally in front of them above an immovable base plate with a specific fiber orientation γ (either -45°, 0°, 45°, see Figure 3). The users' task was to build a pile of four plates with different orientations, to simulate the layering of carbon fiber cloth (see Figure 3, right).

Figure 2 - User interacting with the prototype (visual feedback) (left). User placing a carbon fiber cloth layer on the base (right)

The tasks were verbally given by an instructor (e.g., "*Position your board 45° according to the base fiber orientation*"). Participants had to complete the trials as fast and accurately as possible. In Figure 2, a snapshot from the experiment is given. In the beginning, participants completed a training trial (piling four layers with different fiber cloth orientations) to get familiar with the feedback types and tasks. Each condition consisted of two different base plates with four trials each. The feedback type was randomized. Time and accuracy of the tasks was transparently measured within the application. At the very end, demographic and psychometric data were assessed. The overall duration of each experiment was about 60 minutes.

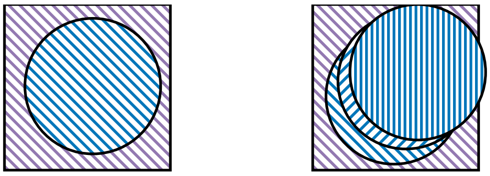

Figure 3 - Starting position (base orientation γ=-45°) (left). Two additional carbon fiber cloth layers have been placed during a task (β_1=90° and β_2=45° relative to base orientation) (right).

6 RESULTS

Results were analyzed by ANOVAs with repeated measurements. The level of significance was set at $p < 0.05$ (outcomes within the less restrictive 10% level were referred to as marginally significant).

6.1 Effects of tutor type

First, we report on the performance outcomes depending on the different tutor types. In Figure 4, outcomes in completion time, in Figure 5 outcomes in accuracy are reported.

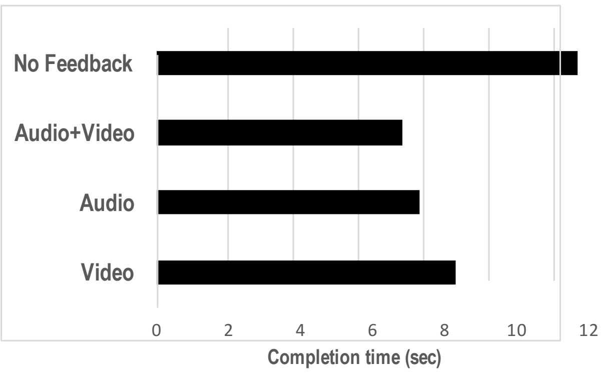

Figure 4 - Speed (sec) depending on tutor type

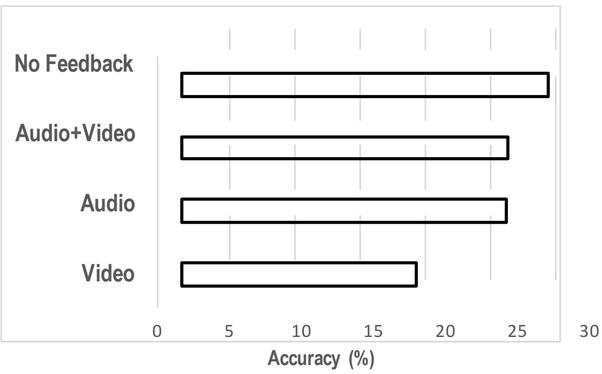

Figure 5 - Accuracy depending on tutor type

A significant main effect on completion times was revealed ($F(3,33)=4.4$; $p < 0.05$). Performance was best (M = 7 s) for the tutor type that combines visual and auditory feedback, followed by audio feedback (M = 7.3 s), and then visual feedback (M = 8.3 s). Performance was worst in the control condition in which no feedback was available (M = 11.7 s).

When looking at accuracy outcomes, a similar picture was found. The combined assistance (visual and auditory) performed best, while the control condition (no tutor) led to the lowest accuracy. Due to huge individual differences, only marginal significance ($F(3,33)=2.3$; $p<0.1$) was found. Results show that the support by tutor assistance benefits the performance in both speed and accuracy, compared to having no tutor at all.

6.2 Effects of user characteristics

In order to analyze effects of spatial ability and technical self-efficacy, two groups were formed by median split: one group each with higher or lower spatial abilities, as well as high and middle technical self-efficacy. In Figure 6, the impact of spatial ability and in Figure 7, the impact of technical self-efficacy on completion times and accuracy are pictured.

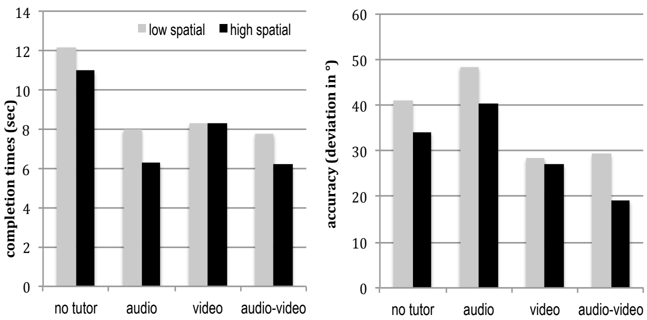

Figure 6 – completion times (left) and accuracy (right) depending on the level of spatial ability

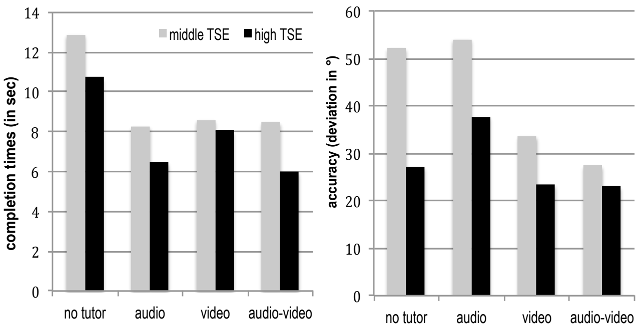

Figure 7 - Completion times (left) and accuracy (right) depending on the level of technical self-efficacy (TSE)

The influence of spatial ability is focused on first. Persons with high spatial abilities are faster and more accurate. The benefit of spatial ability, however, does not vary depending on the type of feedback but represents a general advantage. High self-confidence considerably benefits performance.

Persons with a higher technical self-efficacy are not only faster but also more accurate when aligning the plates. No interaction effect of technical self-efficacy and tutor type is found, showing that the benefit of high self-confidence is a general advantage, not differing with respect to tutor modality.

7 DISCUSSION

In this study, we experimentally addressed the suitability of AR-guided working assistance for the manual quality control in CFPR manufacturing. Two major questions guided this research. One targets the question which modality of feedback leads to the best performance, thereby supporting the workers optimally. Due to the increasing diversity of workers in the production industry, it was a second aim to understand in how far individual abilities of workers might be crucial for quality control and the overall performance. From a huge variety of possible user characteristics that might be important in the CFPR manufacturing quality control, we selected two prominent abilities. One is the spatial visualization ability that might be crucial for the ease and quality of the (spatial) alignment of CFPR plates. The other one – technical self-efficacy – is an affective user factor, which has been found to considerably impact performance outcomes in human-computer interaction [21]. Results show that the feedback is an important supplement for worker support in CFPR manufacturing. In contrast to the condition in which no assistance was given, the availability of any tutor increased performance (independent of the type). This shows that AR-guided tutor assistance is a promising technology in CFPR manufacturing that actually supports workers during the difficult manual quality control in CFPR manufacturing. With respect to the different modalities, the combination of visual and auditory feedback led to the best performance. Apparently, redundancy gains [12] [14] [15] can also be demonstrated in the quality control of CFRP manufacturing. Among the visual and the auditory assistance, a clear advantage of one over the other cannot be revealed – here results show that the completion times are better with the visual type while accuracy outcomes were superior with the auditory version. Although the participants successfully made use of the presented feedback (i.e., drastically increased accuracy), the accuracy of our prototypic system is currently far from acceptable. Even for the most accurate feedback modes (visual+auditory), the average misalignment is far above any accepted error margin. On the basis of the results, we cannot decide the final reasons for the high inaccuracy. Possibly, the participants' strategy while handling the novel prototype might be the reason for this: The instructors frequently observed participants who intentionally misaligned the plates in order to explore how the feedback system will react within or outside of the acceptable limits, which is quite typical for workers with only limited experience. Another reason for the high inaccuracy might be the immature prototype used here. Follow-up studies need to invest in better mechanisms to detect users' hand position (investigating prototypes) or mechanisms that reliably measure the actual misalignment of the fiber. Future studies will continue in this line of research and address more relevant questions in this context. One is that in our study the work with the single tutors was quite short. Also, factory workers which are highly familiar with the CFPR manufacturing process should be included in order to get a realistic picture- A follow up study should therefore be carried out, in which a significantly larger number of trials has to be performed under each feedback condition. Nonetheless, the drastically increased accuracy is a promising indicator that a well-designed worker support system will increase the productivity of CFPR manufacturers. A second line directs to the selection of more experienced workers in order to critically test the usefulness of tutor assistance.

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Experimental Analysis of Damage Development in Carbon Fiber Reinforced Composites under Cyclic Loading

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Abstract
There is a global need to design low weight structures for strategic, business, and social purposes. Reducing weight is critical for improving energy consumption as well as addressing range, performance, size, and cost challenges associated with structural design, especially in the automotive and aerospace industries. In recognition of this need, advances are being made in replacing high strength steels, magnesium and aluminum alloys with carbon fiber reinforced epoxy composites. These have many merits which include weight reduction for lower fuel consumption, resistance to environmental degradation and better aesthetic appeal. For most applications, the carbon fiber reinforced epoxy composites are exposed to cyclic loading leading to fatigue failure. High cycle fatigue in metals usually evolves by the single crack initiation which propagates until catastrophic failure. In contrast to metals, damage development in carbon fiber reinforced epoxy composites occurs in a complex global fashion which occupies an under-researched field. To enable better design, there is a need for a better understanding of carbon fiber reinforced epoxy composites, in particular, damage progression during cyclic loading. The aim of this paper is to investigate damage development during fatigue loading in carbon fiber reinforced epoxy composites. To this end, carbon fiber/epoxy composites produced from a bi-axial carbon material with a fiber volume fraction of 30% were investigated. The specimens were prepared using a hand layup molding technique. The results showed the first two of the three common stages observed during fatigue damage development. The first stage involved rapid damage, followed by stage two which is gradual, and the final stage which is rapid was not observed. The obtained results clearly show the fatigue damage mechanisms in carbon fiber reinforced epoxy composite materials.

Keywords
Carbon Fiber Reinforced Composites (CFRC), Damage Development, Epoxy resin, Low Cycle Fatigue

1 INTRODUCTION

In recent years, there is a growing scientific and economic interest in carbon fiber reinforced composite materials (CFRC). This is due to the quest for low weight structures. CFRCs offer substantial improvement over metals. These improvements include high stiffness-to-weight ratio, low weight, corrosion resistance and high resistance to fatigue. Carbon fiber composites have become indispensable in industries such as sporting, aerospace, marine and automotive [1].

Carbon fiber composites are manufactured by embedding carbon fibers in a polymer matrix.

Focusing on their fatigue behaviour, several studies have been done on the fatigue behaviour of CFRCs. Early notable literature on fatigue response of composites include that of Owen et al [2], followed by Harris et al [3]. These early studies mainly focused on the development of S-N curves. However, damage development under fatigue is very important and acts as a foundation for predicting component life.

Damage development in CFRC materials under fatigue is more complex than that of metals. Damage development in metals is mainly characterised by the propagation of a single crack. The damage process in CFRCs occurs by general degradation with multiple damage mechanisms occurring simultaneously rather than having a single predominant crack [1]. Damage development in composites under cyclic loading may be divided into three stages. Stage one is rapid and involves the formation of multiple crack zones sometimes referred to as damage zones. This initial damage starts early and occurs after a few hundred cycles. This stage involves a sharp decline in the composite stiffness. The second stage is more gradual and involves decline in composite stiffness. More serious damage occurs in the final stage which is also rapid and results in final fracture [4].

There are mainly four damage mechanisms involved in a composite exposed to a cyclic loading. These are matrix cracking, delamination, fiber pullout and fiber-matrix interface failure. Matrix cracking is mainly involved in stage one. Stage two has a mixture of these mechanisms while fiber pullout is dominant in stage three [1, 2, 5].

Liang *et al* [6] investigated damage evolution for four different loading levels monitoring the strain evolution. These loading levels were 0.8, 0.7, 0.6 and 0.5 of the ultimate tensile strength of the material. All three damage stages were observed. Koricho *et al* [7] reported observing the three damage stages at a load level of 75% of the ultimate flexural strength. Rapid damage was observed in the initial stages.

Although analysis has been done on carbon fiber composites exposed to cyclic loadings, detailed analysis, as per authors' knowledge, has not been thorough on damage evolution of biaxial carbon fiber composites exposed to cyclic loading.

2 SPECIMEN FABRICATION

The material used for the investigation was biaxial carbon fiber -45/+45 with a fabric weight of 154 gsm (grams per cubic centimeter). The material used for the matrix phase was a two part epoxy resin, Ampreg 21 resin mixed with 0.33 Ampreg 21 hardener. The laminates were produced using a hand layup moulding process with a stacking sequence $[\pm 45]_7$. This stacking sequence of seven layers gives a fiber content of 30% by volume calculated using the law of mixtures. The plates had a nominal thickness of 4mm.

Specimen fabrication was done using recommendations from ASTM D5687, Standard Guide for Preparation of Flat Composites Panels with Processing Guidelines for Specimen Preparation [8]. During the manufacturing process the two part epoxy resin was mixed by weight and degassed by settling it. A debonding wax was applied to the surface of the mould for easy removal of the plate. Using a paintbrush and small roller, the mixed two part resin was applied to the carbon fiber layer wetting it completely. This was done layer-by-layer until the required number of layers was achieved. The plate was left for 24 hours to dry. A hand layup moulding process was chosen as it enables better control of resin mixing with the fiber compared to other manufacturing processes. Use of a mould also provides better dimensional control.

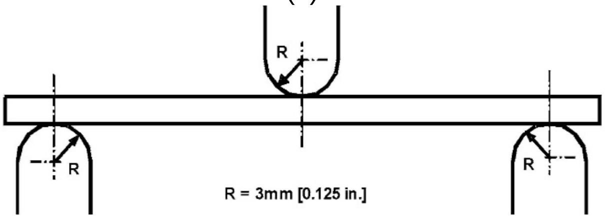
The composite plates were cut into test specimens using Computer Numerical Control (CNC) machining. A 3-D CAD model of the testing plates was initially generated using Solidworks. This CAD model was converted into a G-Code, a numerical control programming language, which is used to drive the CNC machine to do the cutting. After cutting the specimens into required shapes, the specimens were ready for the testing phase.

3 EXPERIMENTAL PROGRAMME

3.1 Static Tensile Tests

In order to determine the stress level to be used in fatigue, it was important to conduct static tensile tests. Displacement control tensile tests were conducted on the Instron 1195 machine driven by Bluehill software 2 (Figure 1 (a)). The machine is equipped with a standard load cell of 100kN capacity and a crosshead displacement measuring device. The tests were conducted according to ASTM D3039, which recommends that failure occurs within 10 mins, hence a stroke rate of 2mm/min was chosen [9]. The tensile test specimen setup is as shown in figure 1 (a).

(a)



(b)

Figure 1: (a) Tensile test setup (b) Three-Point Flexural test schematic

3.2 Flexural Tests

Three point flexural tests were conducted using the same Instron 1195 machine used during the static tensile tests. The specimen geometry is the same as the specimen geometry used for fatigue testing. The tests were again conducted at a stroke rate of 2mm/min. However, this time a 10kN load cell was used in order to improve accuracy of the applied load. The schematic for flexural testing is as shown in Figure 1(b).

3.3 Fatigue Testing

A displacement controlled bending fatigue test was conducted. The machine is displacement controlled by the use of a crank and link mechanism as shown in Figure 2(a). This setup gives a sinusoidal displacement and hence load waveform. 350 Ohm HBM strain gauges with gauge factor of 2.04 were attached to the top of the specimen as shown in Figure 2 (b). These would measure strain variations during fatigue tests. Strain logging was conducted using the National Instruments Compact DAQ with

NI 9234 data acquisition module at a sampling frequency of 200Hz. Fatigue loading was applied under cantilever configuration inducing a stress ratio (R) of -1, tension-compression loading. Load levels applied during the tests were 25% and 50% of ultimate flexural strength of the specimen as obtained experimentally. Load cycling was done at a frequency of 24Hz. All tests were terminated after reaching one million cycles (10^6).

(a) (b)

Figure 2: (a) Fatigue test setup (b) Specimen with attached strain gage

4 RESULTS

4.1 Tensile Static Tests

Figure 3 shows the stress-strain response of the tensile specimens. A total of 6 specimens were tested in accordance with ASTM D3039 [9]. Static tensile tests show two stages of linear response which are shown as region 1 and region 2 in Figure 3. This kind of response is known as bilinear response. According to ASTM D3039, a material exhibiting a bilinear response will have a secondary tensile modulus [9]. The first region repesents the behaviour of the composite prior to first stage failure while the second region is associated with matrix delamination and fiber pullout failure which is dominant in the second stage. Figure 4(a) shows a sample of a failed specimen.

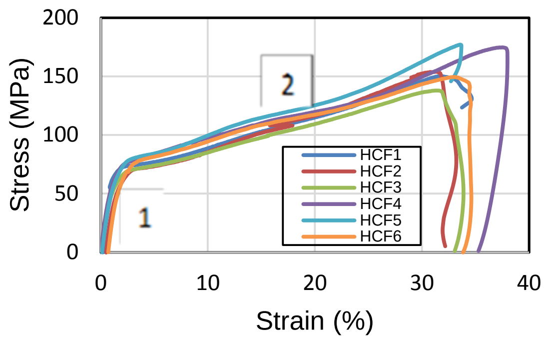
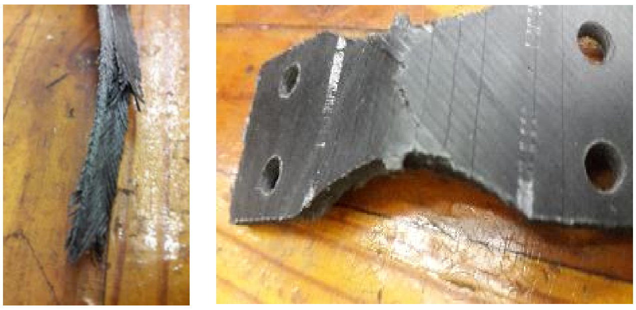


Figure 3: Tensile stress-strain response.

UTS (MPa)	TM1 (GPa)	TM2 (GPa)
157.23	0.828	0.129

Table 1: Tensile test properties

The results of of the tests are summarised in Table 1. The average ultimate tensile strength (UTS) was found to be 157.23 MPa. The average Tensile Moduli (TM) for the two regions are calculated and also presented in Table 1. The difference in tensile moduli for the two regions identifies the two failure modes.



(a) (b)

Figure 4: (a) Failed tensile specimen showing delamination and fiber pullout (b) Failed flexural specimen.

4.2 Flexural Tests

Figure 5 shows the stress-strain response of the biaxial composite under flexural loading. The test was conducted using 3 point bending in accordance with ASTM D7264 [10]. A 0.2% strain offset was used to determine the limit of proportionality by generating a 5th degree polynomial fit (dashed curve) to the curves. A linear curve was constructed parallel to this fit. The point of intersection was taken as the limit. In this case, a single failure mode is observed. The limit was found to be 157.9 MPa. 25% and 50% of this was chosen as the load level to be applied to the material during the cyclic loading.

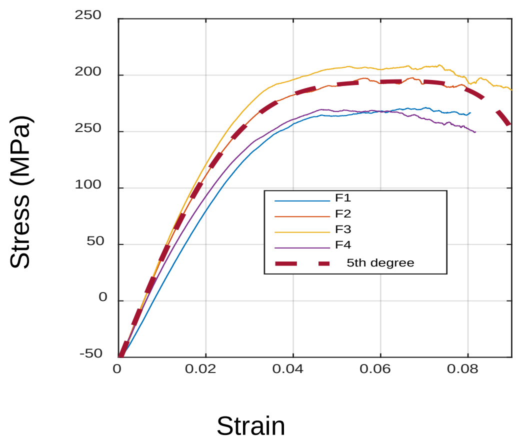


Figure 5: Flexural stress-strain response.

The results obtained from the flexural tests are summarised in Table 2 showing the ultimate flexural strength, the bending modulus and the proportionality limit.

UFS (MPa)	Bending Modulus (GPa)	Proportionality Limit (MPa)
221.1	9.5	157.9

Table 2: Flexural test properties.

4.3 Fatigue Tests

Figure 6 shows the strain evolution as the time proceeds up to the cut off point (10^6 cycles). Both of these show evolution at a loading of 25% of the ultimate flexural strength (UFS). Testing was stopped after one million cycles. Figure 7 shows the stress versus the time at 25% loading level. This is the general cyclic signal obtained from an applied cyclic displacement showing the good quality of the cyclic loading applied to the specimen. Figure 8 shows the extracted measured maximum strains revealing the variation of applied strain with time for the 25% load level. The same is shown in Figure 9 for the 50% load. In this case there is clear sudden failure of the composite at a certain number of cycles.

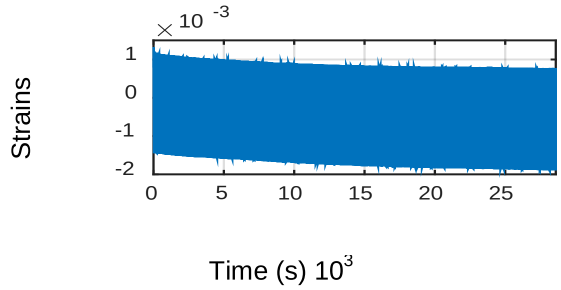


Figure 6: Strain variation as a function of time at 25% UFS load

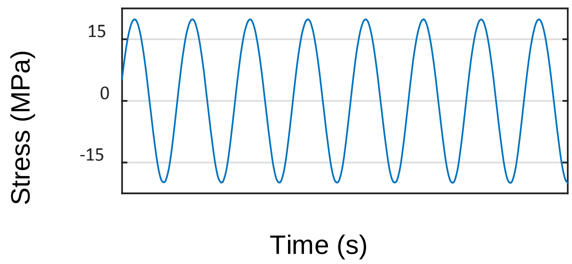


Figure 7: Sample of applied stress signal.

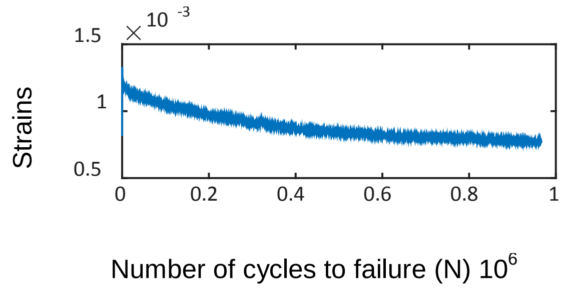


Figure 8: Maximum strains against number of cycles at 25% UFS load.

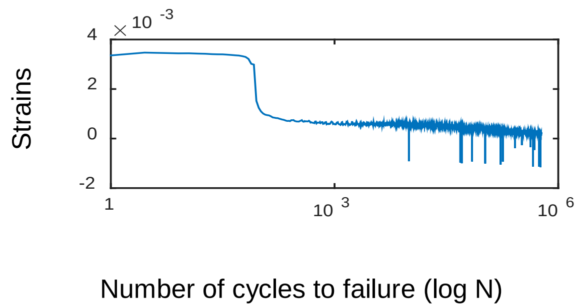


Figure 9: Maxima strains against number of cycles at 50% load.

5 DISCUSSION

Figure 3 clearly shows that the general shape of the load displacement response is consistent among all the specimens which implies that material production and material composition are soundly consistent. The stress-strain curves can be interpreted by dividing them into two linear regions which are indicated as 1 and 2 in Figure 3. The linear regions have different tensile moduli which are 0.828 GPa and 0.129 GPa respectively, showing a bilinear response. This drop in modulus indicates development of damage in the material. The curves are linear to final fracture; there is no indication of large-scale plastic deformation. This is consistent with fiber-matrix interface failure. This is the major reason why the prominent failure mode observed during the tensile testing phase was fiber pull-out as shown in Figure 4(a).

Figure 5 shows the stress-strain response of the material under 3 point bending load. The response under a flexural load has a higher modulus compared to the response under a tensile load. This indicates a significant contribution of the viscoelastic resin. Hence, the resin contributes more under a flexural load which is also supported by the difference in the ultimate tensile strength (UTS) and the ultimate flexural strength (UFS) which are 157.23 MPa and 221.1 MPa respectively.

The response of the material under cyclic loading is indicated in Figure 8 which shows a plot of the variation of maximum strains. At a load level of 25% of UFS, there is a small drop in the strains which is indicative of a change in component stiffness or stress relaxation. A linear fit to the maxima gives a gradient of 0.0000067 strains/number of cycles. This suggests that, for 25% load level, the damage development is gradual and this is as expected since general damage in composites has been reported to be gradual at low load levels [1].

However, there is dramatic damage observed at 50% load level compared to 25% load level. Figure 9 shows a log plot of the strain variation against the number of cycles. Damage occurs early in the fatigue life, within the first 1000 cycles. This is indicated by the sudden drop in the recorded strain. The damage becomes gradual beyond 800 cycles. This indicates the second stage of damage development which is gradual. This stage is observed up to the cut-off point which is one million cycles. The specimen does not reach stage three suggested in literature [1, 7].

6 CONCLUSION

Biaxial carbon fiber/epoxy composites were successfully prepared tested under cantilever bending cyclic loading at a stress ratio of R = -1. Damage was continuously monitored by measuring the strain response of the material at a specific location on the specimen. Based on the results obtained the following conclusions can be made:

- Bending strength is higher than the tensile strength. This shows the anisotropic nature of the composite material. Flexural strength and tensile strength would have been the same if the material was homogeneous.
- Biaxial composites exhibit a bilinear response under a tensile load, which means that they have a secondary tensile modulus. Final failure under a tensile load is fiber pull-out.
- A 25% UFS cyclic loading level does not cause considerable damage to the specimen. However, it exhibits gradual damage development.
- Stage one and stage two damage are observed at a load of 50% of UFS exhibited by a sudden change in stiffness. Stage three damage is not observed.

The results presented are useful in design of composite structural components. Further work needs to be done to get more information for other load levels and continued loading to ultimate failure. Similar work is also recommended for other types of composites.

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8 BIOGRAPHY

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Investigations on Efficient Machining of Titanium Alloys with Cryogenic Cooling

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Abstract
Due to their specific properties titanium alloys have a wide field of application in the modern aviation industry and increasingly in the automotive industry. These lightweight materials exhibit an advantageous strength-to-density ratio and excellent corrosion resistance. However, titanium alloys are difficult to machine. Their low thermal conductivity and high strength cause increased thermo-mechanical loads on the cutting tool. Decreased tool life and consequently, low material removal rates result in extended processing times and increased manufacturing cost. One of the most important parameters is an optimal cooling strategy to achieve high efficiency and process reliability. Thus, the fundamentals are introduced in order to apply cryogenic media to cool the cutting zone. Systematic investigations describe the influence of cryogenic cooling with carbon dioxide (CO_2) and liquid nitrogen (LN_2) on machining various titanium alloys. Based on the studies the potentials of cryogenic cooling in machining these materials will be derived.

Keywords
Titanium, cryogenic machining, cooling

1 INTRODUCTION

Components in aerospace industry are highly sophisticated products concerning operating reliability and service life. Furthermore, these high quality parts have to fulfil the requirements for reductions in mass and emissions while simultaneously increasing the load capacity.

Titanium alloys represent an indispensable group of materials in the modern aviation industry due to their low density in combination with high strength as well as the high corrosion resistance. Moreover these materials show increased fatigue strength at operating temperatures up to 400°C and an improved chemical compatibility with CFRP components compared to aluminum alloys [1], [2], [3]. Hence, titanium alloys are applied for jet engines and airframe components. These usually thin-walled integral parts are machined with high chip removal rates of up to 90% [4]. These high machining rates combined with the poor machinability of titanium alloys and the increased quality requirements represent a key challenge for the machining process. Therefore efficient and economic technologies have to be developed to realize reliable high performance cutting.

2 CHALLENGES IN CONVENTIONAL MACHINING OF TITANIUM ALLOYS

Most of the beneficial material characteristics for the application of titanium alloys negatively influence the machinability resulting in low material removal rates. Machining titanium components requires for example more than ten times of the manufacturing time of a similar aluminum part. The following material properties lead to the challenges in machining titanium alloys [1], [5], [6]:

- High strength
- Low thermal conductivity
- High reactivity with the cutting materials
- Low modulus of elasticity

The high strength of these workpiece materials results in increased thermo-mechanical loads on the cutting tool. Furthermore, the low heat conductivity leads to high temperatures in the cutting zone. About 60% to 80% of the process heat has to be removed via the cutting edge which causes an increase in thermal tool wear [7]. Besides shape and dimensional deviations the low modulus of elasticity effects an enlargement of the contact area between the clearance face of the tool and the workpiece surface which increases friction and tool wear.

The chip formation process of titanium alloys is characterized by segmented chips causing thermo-mechanical alternating stress at the cutting edge.

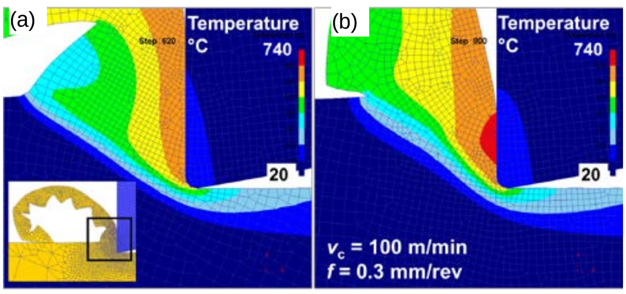

Figure 1 - Chip formation and temperature distribution in the cutting zone, (a) material accumulation at the cutting edge, (b) shearing of chip segment.

Figure 1 shows the characteristic temperature distribution in the cutting zone when machining titanium alloy Ti6Al4V. Maximum temperatures of up to 740°C occur during the shearing of the chip segments along a short contact length between the tool rake face and the chip. Another result of the high temperatures at the cutting edge are diffusion processes and chemical tool wear because of the high reactivity with the cutting materials [3].

Investigations on face milling of the titanium alloy Ti6Al4V were conducted at the Fraunhofer IWU under the conditions of conventional emulsion cooling to demonstrate the influence of the cutting speed, the feed rate and the depth of cut on tool life with regard to increased material removal rates. As shown in Figure 2 the cutting speed has considerable influence on the tool life. Tool wear was rapidly increasing at a cutting speed of more than 70 m/min. Reliable machining with 150 m/min was not possible because of tool failure.

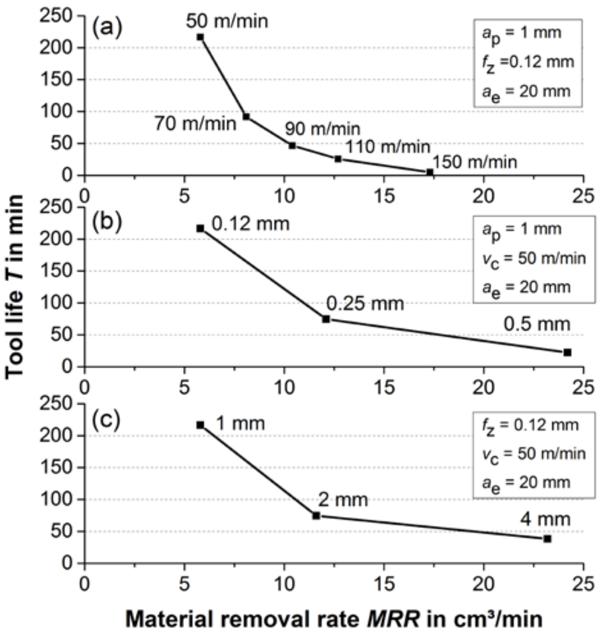

Figure 2 - Influence of various cutting parameter on tool life, (a) cutting speed v_c, (b) feed rate f, (c) depth of cut a_p.

However, process reliability is essential in machining titanium components due to the high material costs and the large size of the parts resulting in machining times of several days. Therefore titanium alloys are machined with low material removal rates to reduce tool wear. This causes long processing times and increased manufacturing cost.

To approach an efficient and reliable cutting process when machining titanium alloys at increased cutting parameters intensively cooling of the cutting zone is a crucial factor. However, conventional cooling methods only show low cooling performance. New cooling strategies such as the application of cryogenic media for process cooling have to be investigated and developed.

3 CRYOGENIC COOLING

Conventional cooling with emulsions is still the most common cooling strategy when machining titanium alloys in industrial practice. However, the application of cooling lubricants leads to high energy consumption, costs for maintenance and disposal as well as to health and environmental risks. Especially in machining titanium alloys temperatures up to 1000°C [7] are generated in the cutting zone. Hence, an efficient cooling strategy is required. The use of media with an increased cooling effect such as cryogenic gases can be beneficial. Cryogenics is defined as the discipline and technology of working at temperatures below 120 K [8]. Cryogenic cooling in connection with a machining process means the application of a cryogenic medium to cool down the cutting zone. Besides liquid nitrogen with a cooling temperature of 77 K (-196°C) also solid carbon dioxide (dry ice) at 194.5 K (-78.5°C) is applied in industry and research to cool the cutting zone. Both media show a different thermodynamic behavior and consequently, have to be distinguished with regard to generated temperatures, supply into the cutting zone and handling.

As liquid nitrogen is fed into the cutting zone with a minimum temperature of -196°C at an ambient pressure the thermal insulation of all supply lines, machine elements with direct contact and the inner coolant supply of the cutting tool is required. This is necessary to ensure a constant cooling jet as well as to avoid damages at the machine tool and hazards for the machine operator [9].

In contrast liquid carbon dioxide (CO_2) is supplied under a pressure of approx. 57 bar and ambient temperature via pressure-resistant pipes through the spindle of the machine tool into the cutting zone. Negative thermal influences on machine elements and supply lines cannot occur as the liquid CO_2 is under pressure. When the liquid medium expands at the outlets of the tool cooling channels the pressure suddenly drops down and a phase transformation takes place from liquid to solid and gaseous CO_2. Due to the Joule-Thomson effect temperatures as low as -78.5°C can be reached [10].

Recent developments combine the cooling effect of a carbon dioxide snow jet with an additional lubricating aerosol referred to as aerosol dry lubrication (ADL). This combination should reduce the friction between cutting tool and workpiece by the application of a very fine oil aerosol with a particle size of approx. 0.1 µm resulting in decreased heat generation [11].

Since the solid carbon dioxide snow as well as the liquid nitrogen sublimate at the high ambient temperature of the cutting zone machining with cryogenic cooling is a dry and residue-free process.

4 APPLICATION OF CRYOGENIC COOLING IN MACHINING TITANIUM ALLOYS

4.1 Longitudinal turning of Ti6Al4V with CO_2 cooling

In the following tool life investigations the effect of cryogenic cooling is compared with high-pressure cooling. The tests were conducted in longitudinal turning of the α+β alloy Ti6Al4V which is characterized by a tensile strength R_m of 900 N/mm² and a low thermal heat conductivity of 6.6 W/m·K. The high-pressure coolant jet and the cryogenic CO_2 are supplied through the cutting tool directly into the cutting zone. A third strategy is the combination of CO_2 cooling with a lubricating aerosol (ADL), both supplied via external nozzles. Coated carbide inserts were selected.

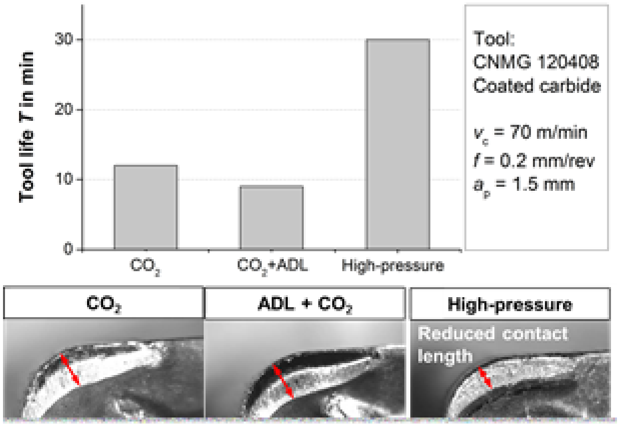

Figure 3 - Tool life and wear mechanisms in turning Ti6Al4V with various cooling strategies.

The achieved tool life with the varied cooling strategies is presented in Figure 3. High-pressure cooling with 80 bar results in the highest tool life of 30 minutes. The cryogenic cooling strategies with and without additional lubrication only reach a tool life of 9 to 12 minutes, although the measured temperatures at the cutting insert were reduced by 20 K. It can be assumed that the high-pressure coolant jet reaches the contact zone between chip and tool rake face much better and cools the cutting zone more intensively. This assumption is supported by the wear pattern at the tool rake face. Thermal tool wear was the limiting factor in turning Ti6Al4V. As shown in Figure 3 the tool wear at the rake face was strong crater wear causing chipping of the cutting edge as the dominating failure mechanism. With high-pressure cooling the contact length is reduced, crater wear is decreased and longer tool life can be realized. At the end of all tool life tests the flank wear *VB* was less than 0.3 mm.

To evaluate the energy consumption of the cooling strategies the specific energy consumption has to be determined by the ratio of the required total power to the material removal rate.

When comparing the specific energy consumption of all cooling strategies it can be seen that the application of cryogenic CO_2 cooling with and without additional lubrication results in savings of more than 60% compared to high-pressure cooling (Figure 4).

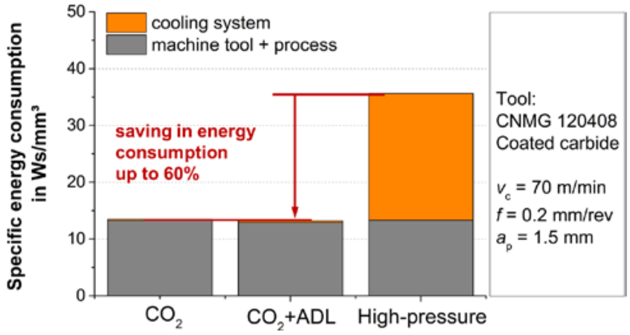

Figure 4 - Specific energy consumption in turning Ti6Al4V.

The investigations on the influence of cryogenic cooling with CO_2 on the tool life showed that in longitudinal turning of the titanium alloy Ti6Al4V the crucial factor is the intense cooling of the cutting edge. Hence, further developments in tool design have to be done to direct the cryogenic media as close as possible to the cutting edge to use the high cooling effect.

4.2 Longitudinal turning of Ti-5553 with various cryogenic media

Besides the most common titanium alloy Ti6Al4V the near β-titanium alloy Ti5Al5V5Mo3Cr (Ti-5553) becomes more important due to the increased high-temperature strength and a high tensile strength of of 1300 N/mm². The investigations in this chapter show the influence of different cryogenic cooling strategies on tool wear and tool life in comparison with various conventional cooling strategies.

4.2.1 Machining of Ti-5553 with LN_2 cooling

The tests in longitudinal turning were carried out with a cemented carbide cutting insert with an outlet for the liquid nitrogen on the rake face. The turning chisel is adapted with a thermally insulated inner coolant supply. The LN_2 cooling was compared to conventional emulsion cooling. Turning tests were stopped when a flank wear of VB = 0.3 mm or tool failure occurred. The cutting speed was varied between 50 - 100 m/min. The feed rate f = 0.1 mm and the depth of cut a_p = 1 mm were kept constant.

Measurements of the temperatures at the cutting tool and the workpiece show that with emulsion cooling the temperatures reach a level of approx. 23°C. With LN_2 cooling the workpiece is cooled down by 8 K. In contrast, the tool temperature is drastically reduced to more than -110°C (Figure 5). Consequently, a high cooling effect can be provided by using liquid nitrogen.

Adhesions on the workpiece surface appear with both cooling strategies leading to high surface roughness values up to Rz = 17 µm.

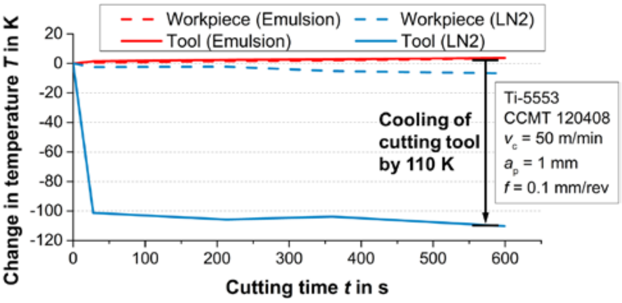

Figure 5 - Thermal behavior of workpiece and cutting tool.

Figure 6 presents the development of the tool wear depending on the processing time. The flank wear increases slightly and the formation of built up edges occurs with both cooling strategies at a cutting speed of 50 and 75 m/min. With conventional emulsion cooling the cutting edge was subjected to notch wear which was the reason for the termination of the tests. The notch wear mechanism can be prevented by applying cryogenic cooling with LN_2. Further increase in cutting speed up to 100 m/min leads to short tool life as a result of tool failure.

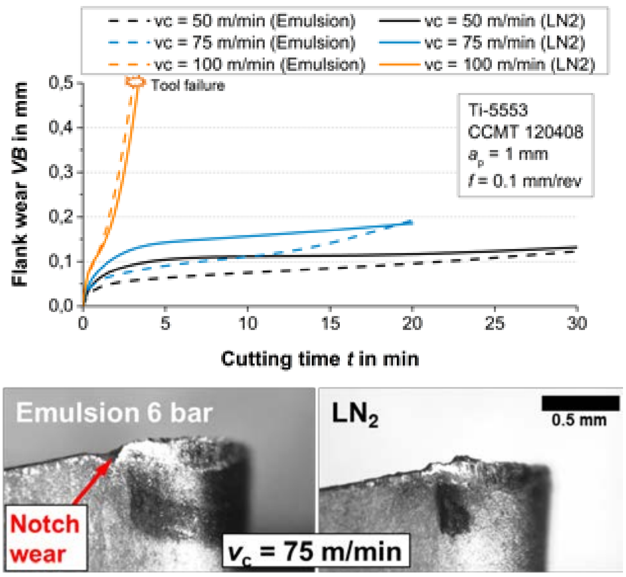

Figure 6 - Tool wear behavior in machining Ti-5553 with cryogenic LN_2 cooling and emulsion cooling.

The application of liquid nitrogen cooling in longitudinal turning of Ti-5553 offers the potential of a dry machining process of titanium parts. However, the type of supply of the cryogenic medium into the cutting zone has to be improved as well as the cutting materials need to be optimized with regard to low temperature properties. Furthermore, additional lubrication is required concerning an improvement in surface quality.

4.2.2 Machining of Ti-5553 with CO_2 cooling

Further machining tests in longitudinal turning were carried out with the same alloy Ti-5553. Four different types of cooling strategies were investigated with regard to their influence on tool wear, tool life, surface integrity, occurring chip morphology and specific energy consumption. Conventional emulsion cooling with a pressure of 6 bar, high-pressure cooling (HP) with 80 bar and CO_2 cooling were supplied through nozzles in the tool holder while the combination of CO_2 cooling and aerosol dry lubrication were fed via external nozzles (Figure 7).

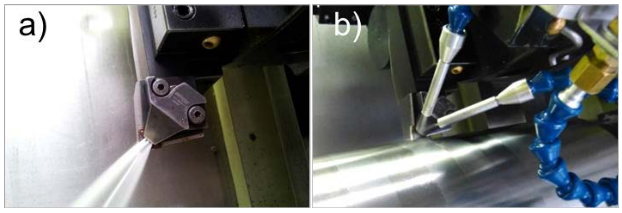

Figure 7 - Experimental setup, (a) through tool supply, (b) external supply of ADL with CO_2 cooling via nozzles.

The cutting inserts of type CNMG120408 consist of cemented carbide with a multilayer coating. The following table 1 summarizes the tested cutting conditions which were identified in preliminary investigations. The turning tests were aborted when a maximum flank wear VB_{max} of 0.3 mm or a machining time of 15 minutes were reached. After the first test with a cutting speed of 50 m/min no differences in tool wear behavior could be observed within this time. In order to investigate increased material removal rates and due to the high material costs this test series was stop after 15 minutes and the higher cutting speed of 75 m/min was tested until a maximum machining time of 30 minutes.

Table 1 - Design of experiments.

	Cooling strategy			
	Emulsion 6 bar	HP 80 bar	CO_2 cooling	CO_2 + ADL
Type of supply	Through tool nozzles			external nozzles
v_c in m/min	50, 75, 100			
f in mm/rev	0.1			
a_p in mm	1.5			

The tool life with cryogenic CO_2 cooling and high-pressure cooling is comparable for all investigated cutting speeds. At a cutting speed of 75 m/min a tool life of 30 minutes and with 100 m/min a tool life of 15 minutes can be reached (Figure 8). Conventional emulsion cooling exhibits a lower cooling effect. Due to the low pressure of the coolant it cannot reliably get into the contact zone between cutting edge and chip. The lowest tool life with a cutting speed of 75 m/min was reached with the CO_2 cooling in combination with the aerosol dry lubrication. The reason for this low performance was the type of supply of the media via external nozzles so that the media do not get as close as possible into the contact zone which leads to an insufficient cooling and lubrication effect.

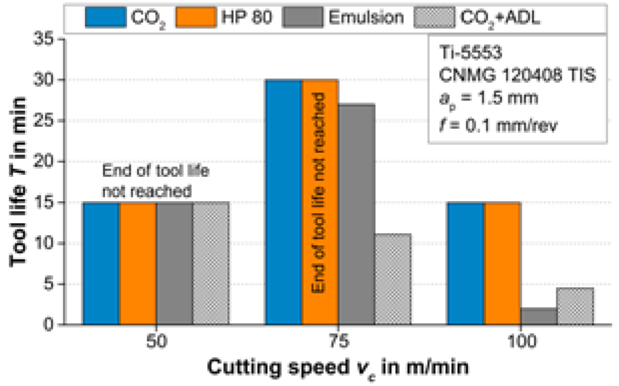

Figure 8 - Tool life in longitudinal turning Ti-5553 with the tested cooling strategies

Figure 9 represents the tool wear behavior for the different cooling conditions with a cutting speed of 75 m/min. The abort criterion of a flank wear at the clearance face of 0.3 mm was not achieved for any cooling strategy. The formation of small built up edges occurs when using high-pressure cooling and CO_2 cooling. However, this wear process does not result in tool failure within a machining time of 30 minutes. In contrast, the dominating wear mechanism in machining with conventional emulsion cooling as well as with external CO_2 cooling with aerosol support is characterized by chipping of the cutting edge due to strong formation of built up edges and notch wear.

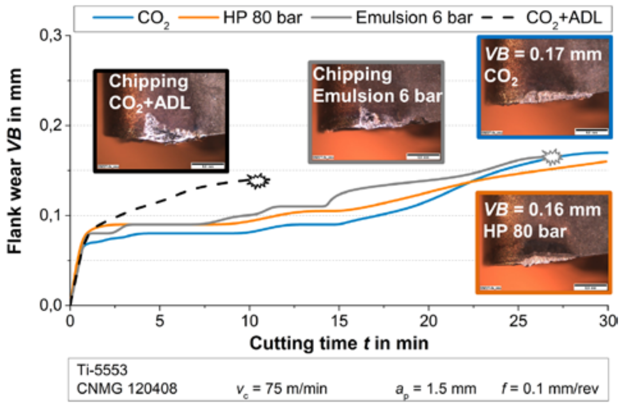

Figure 9 - Tool wear behavior in turning Ti-5553 with various cooling strategies

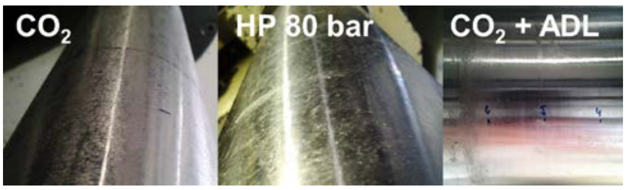

Figure 10 - Material adhesions on workpiece surface with CO_2 cooling and high-pressure cooling (v_c = 75 m/min)

A reasonable comparison of the surface roughness was not possible due to the strong material adhesions on the workpiece surface under almost all cooling conditions (Figure 10). Only with the combination of CO_2 cooling with the very fine lubricating aerosol (ADL) this phenomenon could be reduced. It can be concluded that the lubrication has a positive effect on the surface integrity.

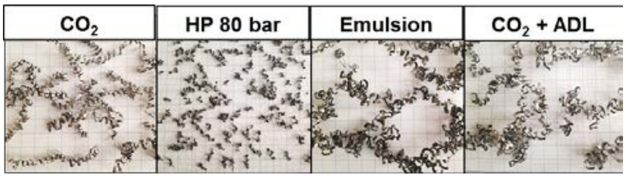

Figure 11 - Chip breaking behavior with the various cooling strategies (v_c = 75 m/min)

The investigated cooling strategies show an influence on the chip breaking behaviour as well (Figure 11). The best chip control is achieved with the high-pressure cooling jet as the hydrodynamic wedge formed between rake face and chip leads to a higher bending moment resulting in better chip breaking. Short arc chips and helical chips are formed. Emulsion cooling and CO_2 with aerosol dry lubrication generate snarled helical chips which pose a risk concerning the process reliability. The application of CO_2 cooling induces the formation of long helical chips.

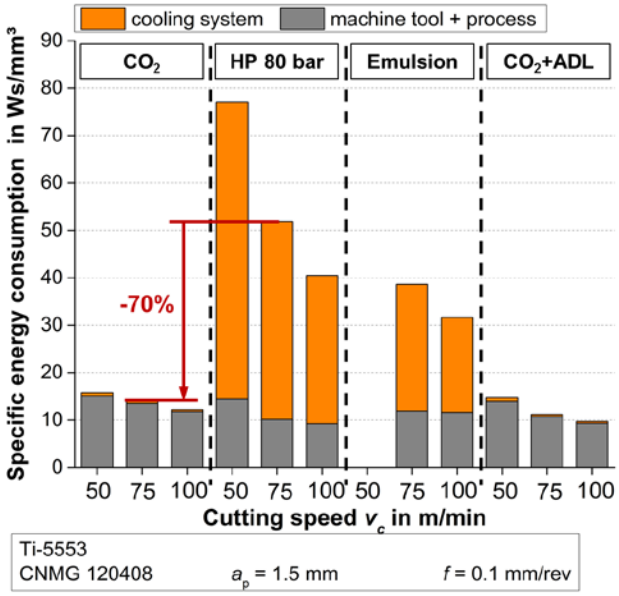

Figure 12 - Specific energy consumption depending on cooling strategy and cutting speed.

The specific energy consumption for the machining process and the machine tool is comparable for all cooling strategies (Figure 12). An increase in cutting speed results in lower energy consumption due to higher realized material removal rates. When considering the specific energy consumption of the cooling devices the highest the energy-saving potential of up to 70% is provided by the application of the cryogenic cooling system.

5 CONCLUSIONS

The application of cryogenic gases as a coolant enables intensive cooling of cutting zone resulting in increased tool life comparable to high-pressure cooling and simultaneously decreased energy consumption. Thanks to the sublimation of the media a dry and residue-free cutting process can be achieved. However, to realize a stable and reliable cooling process an appropriate supply of the cooling medium into the zone between the tool rake face and the chip has to be ensured. Furthermore, the combination with additional lubricants has to be investigated in order to improve the surface integrity of the machined workpieces. With optimally adjusted cooling parameters cryogenic cooling offers the potential of efficient high-performance and high-speed cutting of titanium alloys.

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7 BIOGRAPHY

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Minimum Quantity Lubrication (MQL) Assisted Machining of Grade-4 Titanium

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Abstract
This paper presents the results of an experimental investigation for turning of Grade-4 titanium with carbide cutting tool inserts with minimum quantity lubrication (MQL). Experiments were designed based on Taguchi's L_9 orthogonal array. The MQL parameters of flow rate (50-70-90 mL/hr); nozzle distance (20-30-40 mm) and air pressure (4-5-6 bar) were varied for three different levels each. Cutting speed, feed and depth of cut were fixed at 125 m/min; 0.2 mm/rev and 1 mm respectively. The grey relational method in conjunction with the Taguchi technique was used for optimizing the MQL parameters. The nozzle distance was recognized as the most significant parameter. The data further indicated that the optimum MQL parameters were a flow rate of 70 mL/hr, nozzle distance of 30 mm and air pressure of 6 bar. When compared to dry and wet cutting conditions MQL was shown to have significant advantages.

Keywords
Minimum quantity lubrication, Green machining, Taguchi robust design, Tool wear

1 INTRODUCTION

Environment awareness is of utmost importance to all socially responsible manufacturers. In order to ensure global competitiveness, manufacturers need to comply with various strict environmental regulations. To maintain economic growth and product quality while adhering to these regulations entails the adoption of sustainable manufacturing techniques. These techniques include; optimizing the machining process parameters; appropriate tool geometry, material and/or coating; employing advanced and hybrid machining processes; and using advanced lubrication/cooling techniques such as minimum quantity lubrication (MQL), cryogenic cooling and dry machining etc [1-3]. The effective utilization of these techniques may assist to achieve resource, energy and cost efficiency while simultaneously addressing environment concerns such as sustainability and pollution.

The 'wonder metal' titanium and its alloys are extensively used for specialized applications in aerospace, medical and general industry because of its superior strength to weight ratio, exceptional corrosion and erosion resistance, bio-compatibility, high fatigue strength and attractive mechanical properties [4, 5]. Commercially pure titanium Grade-4 is a promising material for biomedical applications especially dental implants. Many of its applications require significant machining. It is however generally regarded as a difficult to machine material because of certain inherent properties. These are briefly summarized as: a low thermal conductivity that inhibits heat dissipation within the machining zone and therefore creating high thermal gradients which leads to rapid tool wear and in some cases catastrophic tool failure; a low elastic modulus (effectively 50% of steel) implying large deflections of the workpiece during machining and thereby increases chatter, vibration and rubbing leading to elevated temperatures which in turn may cause poor surface finish; the high chemical reactivity especially at elevated temperatures leads to tool-workpiece interactions such as localized adhesion implying increased wear, chipping and eventually tool failure [5, 6].

The problem of tool failure during machining can be addressed primarily in two ways; careful selection of appropriate tool material, geometry and coating and/or employing a suitable lubrication/cooling technique with appropriate lubricant (cutting fluid).

The use of large amounts of mineral-based harmful cutting fluids during traditional cooling i.e. flood or wet cooling techniques may adversely impact the environment because it may lead to increased ground contamination, implies increased energy consumption, increased wet chip handling and waste disposal, and may increase potential health and safety issues [7, 8]. To address these issues, there has been a steadily increasing interest in performing machining operations dry or near-dry. Minimum quantity lubrication (MQL) is a micro-lubrication technique that facilitates near-dry machining [8, 9].Micro-lubrication implies the elimination of large quantities of water and mineral oil-based cutting fluids and replacing them with a small quantity of lubricant (10-200 mL/hr flow rate) mixed with and transported by air. Vegetable oils, synthetic esters and fatty alcohols are typically used as lubricant which is mostly environmentally friendly and biodegradable and therefore also less harmful to humans during use. Moreover, supplying a small amount of cutting fluid consumes less power and thus reduces the cost of machining also. The main benefit of MQL is that it primarily focuses on improving the frictional behaviour therefore controlling the heat generation at its source rather than just trying to remove as much heat as possible such as conventional cooling does. This results in improved tool life and good workpiece surface integrity. Metal chips produced during MQL machining are nearly dry and are easy to recycle [8-10].

However, the machinability and part quality (in case of titanium also) depends largely on optimizing the MQL process parameters that includes the type and flow rate of the lubricant and nozzle position and pressure [11-14].

This paper reports some preliminary investigations based on the effects and selection of optimum MQL parameters namely flow rate, nozzle distance and air pressure for further detailed research work while turning Grade-4 titanium at different combinations of machining parameters (i.e. cutting speed, feed and depth of cut).

Surface roughness of the workpiece, power consumption during machining, and tool (flank) wear were considered as indicative of machinability.

The main objectives of this research work are:

1. To investigate the effect of MQL process parameters on the machinability of Grade-4 titanium.

2. To identify the levels at which certain MQL process parameters are to be fixed for subsequent experimentation.

3. To find the optimal combination of input process parameters for obtaining improved machinability indicators (multiple responses).

Experiments were designed and conducted based on *Taguchi's robust design* of experiments method and utilizing the L_9 orthogonal array. The statistical *grey relational analysis* technique was employed to perform optimization. In addition, this research is also accompanied by a limited comparative study indicating the advantages of MQL when compared to dry and wet cutting when machining Grade-4 titanium.

2 TAGUCHI METHOD AND GREY RELATIONAL THEORY

The Taguchi method[15-17] is a variance reduction technique which can improve the quality of a system at minimum cost. An orthogonal array (OA) is used to reduce the number of experiments which will have time and cost benefits. In the present case based on the three response parameters each having three levels, L_9 OA was chosen which cut down the number of experiments from 27 (3^3-Full Factorial design) to 9. Itis important to ensure that the resultant functionality resembles as closely as possible the ideal function. It is therefore crucial to develop a means for measuring the deviation between the actual and the ideal cases. Hence, Taguchi employs signal to noise (S/N) ratio to measure the performance of the process response. S/N ratio being the ratio of mean to standard deviation that can effectively consider the variation encountered in a set of trials. Again based on the objective of the experiment, S/N ratio characteristics can be categorized into three criteria: lower-is-better(LB), higher-is-better (HB) and nominal-is-best (NB).

As one of the main objectives of the present research work was to determine the machining conditions required to obtain improved machinability in terms of minimum surface roughness of the workpiece, least power consumption and lowest tool wear in the turning of Grade-4 titanium. Therefore, the quality characteristics of lower-is-better was implemented for all the above stated response parameters. The S/N ratio of the lower-is-better characteristic can be expressed as follows:

$$S/_N = -10\ \log\left(\frac{1}{n}\sum\frac{1}{y_{ij}^2}\right) \quad (1)$$

Where y_{ij} is the observed data i.e. response of ith trial of jth dependent level and n is the number of observations for a particular experimental combination or simply called experimental replication.

Grey relational analysis based on the grey system is a statistical technique to solve multi response optimization problems. The grey system theory was first proposed by Deng in 1989 [18]. Afterwards, he also proposed grey relational analysis (GRA) in the grey theory that was proved to be an accurate method for multiple attribute decision making problems. The GRA method is based on the minimization of maximum distance from the ideal referential alternative. The aim of GRA is to investigate the factors that affect the system. The method is based on finding the relationships of both independent and interrelating data series. By finding the GRA mathematically, the grey relational grade (GRG) can be used to evaluate the relational level between referential series and each comparative series. This analysis consists of the following steps [18-20]:

Step 1: Transform the responses into the S/N ratio using the appropriate equation depending on the quality characteristics.

Step 2: Normalize the S/N ratio to distribute the data evenly and scale it into an acceptable range for further analysis by applying the appropriate equation:

For lower-is-better (the present case)

$$Z_{ij} = \left(\max\ y_{ij} - y_{ij}\right)/\left(\max\ y_{ij} - \min y_{ij}\right) \quad (2)$$

Where $Z_{ij}$is the normalized value of ith trial for jth dependent response.

Step 3: Compute the grey relational coefficient (GRC) for the normalized S/N ratio values as per the following equations:

$$\mathrm{GRC_{ij}} = (\Delta_{\min} + r\,\Delta_{\max})/(\Delta_{0j} + r\,\Delta_{\max}) \qquad (3)$$

Where Δ_{min} and Δ_{max} are the minimum and maximum normalized values of S/N ratio among all experimental combinations for a particular response, $\Delta_{0J} = \|1 - Z_{ij}\|$, and r is the distinguishing coefficient which is used to adjust the difference of the relational coefficient and usually lies between 0 and 1. The distinguishing coefficient reduces the effect of Δ_{max} when it gets too big, enlarging the different significance of the relational coefficient. The suggested value of r is 0.5 due to the moderate distinguishing effects and good stability of the outcomes.

Step 4: Compute the grey relational grade by using:

$$G_n = \frac{1}{n}\sum GRC_{ij} \qquad (4)$$

Where n is the number of performance characteristics (4 in the present case). The grey relational grade is simply calculated by averaging the grey relational coefficients. The grey relational grade is treated as the overall response of the process instead of the multiple responses individually. The higher the grey relational grade, the closer is the experimental value to the ideal nominal value. Thus, a higher grade indicates that the corresponding parameter combination is closer to the optimal.

Step 5: To compute the significant parameter based on the largest difference of maximum and minimum grades among all the levels of that parameter.

Step 6: Selecting the optimal levels of process parameters corresponding to the level of a parameter having highest grade.

Step 7: to conduct a confirmation experiment, verify the optimal process parameter settings and optimization by comparing the results with that of the experimental combination corresponding to the highest grey relational grade.

3 EXPERIMENTAL DETAILS

In the present study, Grade-4 titanium is used as the workpiece material. Experiments were performed on a manual lathe using a rhomboid shaped carbide tool insert. An MQL device (*Producut APL 005/03)* was mounted on the machine tool to supply environmentally friendly lubricant which is a blend of natural, synthetic and sulphurized esters with anti-wear additives and anti-oxidants with flow rate ranging from 10 mL/hr to 540 mL/hr through a micro nozzle at pressure ranges between 1 and 6 bars. Figure 1 illustrates the experimental setup whereas Table 1 presents the details of machining parameters used in the present research work.

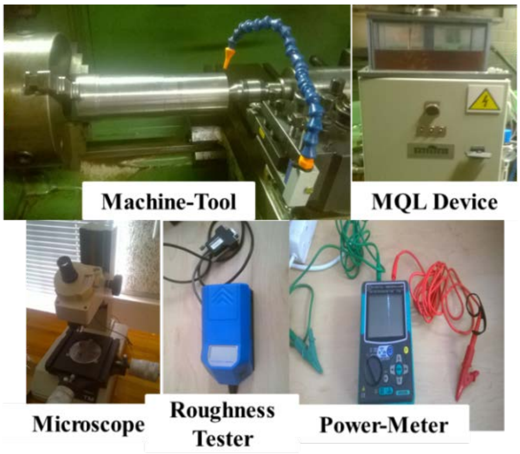

Figure 1 - Experimental setup.

Variable parameters	Symbol	Unit	Level		
			-1	**0**	**1**
Flow rate	F_L	mL/hr	50	70	90
Nozzle distance	N_D	mm	20	30	40
Air pressure	N_P	bar	4	5	6
Fixed parameters: Cutting speed-125 m/min; Feed rate-0.2 mm/rev; Depth of cut-1 mm					
Properties of Lubricant: Pour point- 8^0C; flash point- >290^0C; kinematic viscosity- 39.11 mm^2/s at 40^0C; density- 0.9199 g/cm^3 at 20^0 C					

Table 1 - Details of parameters used in the experimentation.

The effect of the three most important MQL parameters i.e. flow rate, nozzle distance and air pressure were evaluated at three levels each. These levels were selected based on conducting some preliminary experiments, machining constraints and recommendations of the MQL device manufacturer. Cutting speed, feed and depth of cut were fixed at the values considered as the median levels for a subsequent next phase of experimentation. A cutting speed of 125 m/min implies a speed in the transition zone (in between the ranges of conventional and high speed machining)for machining of titanium [21]. Workpiece surface roughness (average and maximum roughness), power consumption and tool wear were the main output/response parameters. The run time for each of nine experiments was fixed at 5 min in order to get a significant amount of tool wear.

The total power consumption during each experimental run is the sum of total power consumption of the lathe during actual machining, power consumption by the MQL device set to deliver lubricant at the particular flow rate value and the power consumption of the air compressor associated with the MQL device at the particular pressure. The power consumption of the lathe was measured in time whereas the power consumption of the MQL device and compressor was calculated using the MQL operation parameters based on actual calibration power assessment tests. Two important surface roughness parameters average roughness 'R_a' and maximum roughness 'R_{max}' (distance between highest peak to deepest valley) were considered to describe the work piece surface quality. Roughness measurements were done by a handheld roughness tester (*Hommel*T500) set at 0.8 mm cut-off length and 4 mm evaluation length, and by tracing the work surface along the tool feed direction. Three measurements were taken for each experimental run and the average value was considered for further analysis.

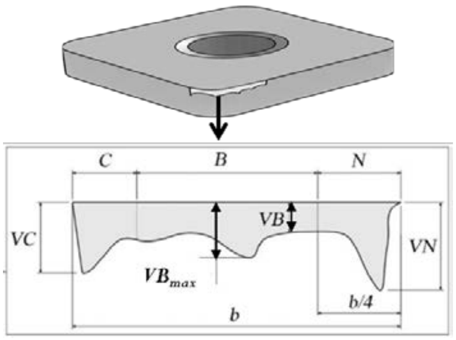

Figure 2- Flank wear in carbide tools: VB-average width of flank wear; VB_{max}- maximum width of flank wear in zone B; Notch wear VN in zone N and Nose wear VC in zone C

Flank wear was selected as the criterion of tool wear and measured with a tool maker's microscope. The tool was deemed failed when the maximum flank wear 'VB_{max}' (see Figure 2) reached 0.6 mm as recommended by the ISO-standard [22].

4.1 Effect of flow rate

During MQL assisted machining, the number of droplets, droplet size and distribution are the main parameters that determine mist quality [23]. Efficient MQL implies the maximum number of droplets to fully cover the surface area between the tool-chip interface. This is usually ensured by high flow rates. Therefore, improved workpiece surface roughness and lower tool wear were obtained with high flow rate (see Fig. 3).

The high tool wear at the lowest flow rate is due to insufficient lubricant (oil droplets) to reduce the friction and thereby heat generated between tool-chip and tool-workpiece interfaces. The lower power consumption at the lowest flow rate is due to the lower consumption of the MQL system at lower flow rates. The difference between the power consumption for the lowest and highest value flow rates is not significant.

4.2 Effect of nozzle distance

The effect of the nozzle distance on the machinability parameters investigated is presented in Figure 4.The nozzle distance has an effect on the diffusive nature of the spray over the travel distance, the chip breakage and droplet penetration into the interface. A shorter nozzle distance is preferable as it ensures high mist velocity [24]. In the present case the shorter nozzle distance ensured the presence of a fully enveloped mist to the target surface and consequently resulted in minimum roughness and low tool wear.

Expt. No.	F_L (mL/hr)	N_D (mm)	N_P (bar)	Surface roughness (µm)		Power consumption (kW)	Flank wear (mm)
				R_a	R_{max}		
1	50	20	4	0.617	4.6	2.0	.557
2	50	30	5	0.798	5.41	2.083	.302
3	50	40	6	0.66	4.51	2.059	1.700
4	70	20	6	0.733	4.94	2.143	1.015
5	70	30	4	1.24	8.56	2.115	.800
6	70	40	5	0.877	6.4	2.279	.907
7	90	20	5	0.463	3.5	2.188	.612
8	90	30	6	0.997	8.64	2.293	.400
9	90	40	4	0.613	6.72	2.226	1.175

Table 2 - Experimental design matrix and results.

4 RESULTS AND DISCUSSION

The experimental results for the machinability descriptors (response parameters) evaluated are presented in Table 2for each experimental run as designed based on the Taguchi technique for different combinations of input parameters. Table 3 presents the values of S/N ratios calculated using Eq. 1 along with corresponding grey relational coefficients and grades for each experimental run.

Longer spray distances implies lower pressure intensity of the jet and therefore lower lubrication efficiency causing an increase in cutting force and consequently power consumption.

4.3 Effect of nozzle distance

The effect of the nozzle distance on the machinability parameters investigated is presented in Figure 4.The nozzle distance has an effect on the diffusive nature of the spray over the travel distance,

Expt. No.	Surface roughness				Power Consumption		Flank Wear		GRADE
	R_a		R_{max}						
	S/N ratio	GRC	S/N ratio	GRC	S/N ratio	GRC	S/N ratio	GRC	
1	4.194	0.4135	-13.255	0.4175	-6.0205	0.3333	5.0828	0.4363	0.4002
2	1.959	0.5274	-14.663	0.4906	-6.3737	0.4157	10.399	0.3333	0.4417
3	3.609	0.4382	-13.083	0.4098	-6.2731	0.3884	-4.6	1	0.5591
4	2.697	0.4835	-13.874	0.5595	-6.6204	0.5025	-0.129	0.6257	0.5428
5	-1.868	1	-18.649	0.9784	-6.5062	0.4582	1.938	0.5341	0.7426
6	1.140	0.5868	-16.123	0.6002	-7.1548	0.9177	0.847	0.5787	0.6708
7	6.688	0.3333	-10.881	0.3333	-6.8009	0.5931	4.264	0.4906	0.4375
8	0.026	0.6925	-18.730	1	-7.2080	1	7.958	0.3736	0.7665
9	4.250	0.4111	-16.547	0.6418	-6.9505	0.6974	-1.4	0.7002	0.6126

Table 3 - Signal to noise ratio and grey relational coefficient for various response parameters and grey relational grade

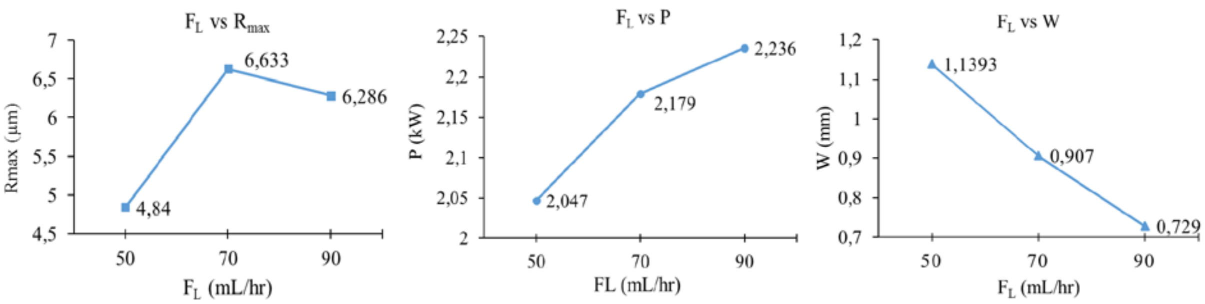

Figure 3- Effect of flow rate on (a) surface roughness; (b) power consumption; and (c) tool wear

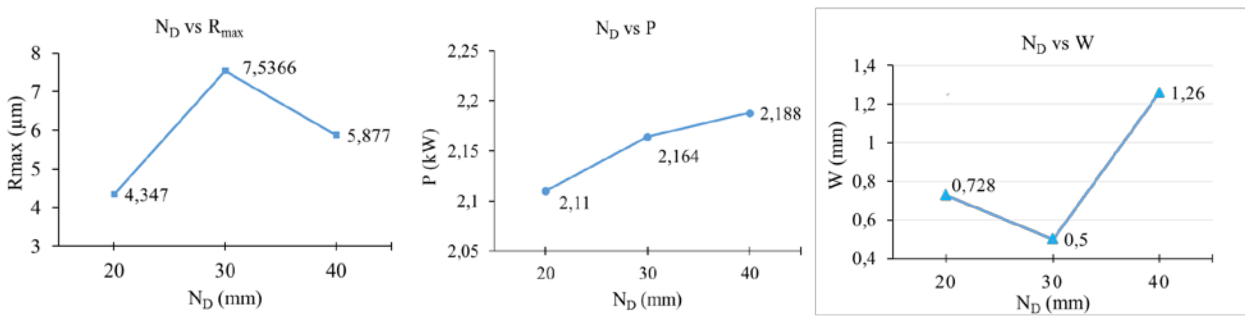

Figure 4- Effect of nozzle distance on (a) surface roughness; (b) power consumption; and (c) tool wear

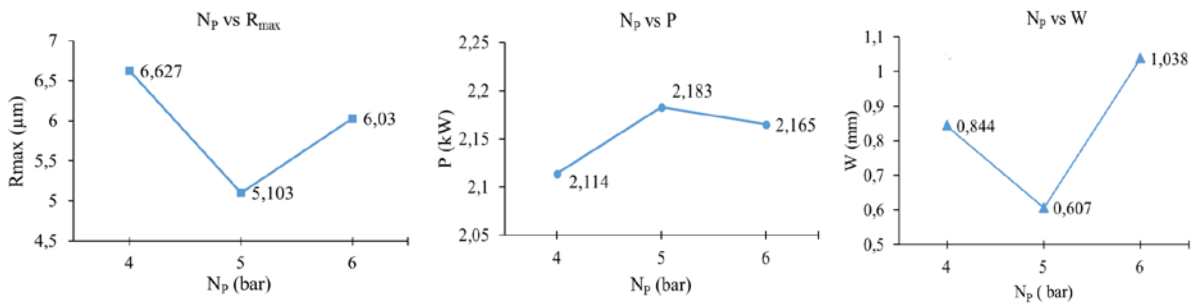

Figure 5- Effect of air pressure on (a) surface roughness; (b) power consumption; and (c) tool wear

the chip breakage and droplet penetration into the interface. A shorter nozzle distance is preferable as it ensures high mist velocity [24]. In the present case the shorter nozzle distance ensured the presence of a fully enveloped mist to the target surface and consequently resulted in minimum roughness and low tool wear.

Longer spray distances implies lower pressure intensity of the jet and therefore lower lubrication efficiency causing an increase in cutting force and consequently power consumption.

4.4 Effect of air pressure

High air pressure helps the oil mist to penetrate into the cutting zone. Therefore the lowest air pressure resulted in increased roughness and tool wear for the present case.

The highest air pressure is also not optimal. High air pressure may lead to droplets bouncing off the work and tool surfaces because of conservation of momentum effects [12] thereby not being available for effective lubrication and consequently resulting in higher roughness and tool wear.

Medium air pressure probably results in a fully uniform fluid film that provides sufficient cooling and lubrication, which resulted in best surface finish and lowest tool wear (see Fig. 5). The lowest pressure probably implies a non-uniform film and consequently higher roughness and wear.

Higher grey relational grades, as presented in Table 3,imply that the corresponding experimental result is closer to the ideal normalized value. Consequently experiment no. 8 displays the best performance characteristics amongst all the experiments.

5 OPTIMIZATION AND COMPARATIVE STUDY

The average grey relational grade for each level of a parameter was calculated by using the values of the grades presented in Table 3. A high relational grade results in good performance of the parameter at said level. Therefore, the optimal level of the parameter is the level with the highest average grey relational grade value. The highest average grey relational grade for the flow rate is at 70 mL/hr, for nozzle distance it is at 30 mm and for pressure it is at 6 bar. A validation (confirmation) experiment was conducted at the optimum parameter combination to verify the optimization. Table 4 presents the results of the optimization i.e. the values of output parameters at optimal combination of input parameters. When comparing these values with those obtained corresponding to experiment no. 8,having the highest grey relational grade, it is found that the optimum values are much improved implying that the results were optimized indeed.

Optimal parameters	**Optimal responses**			
Machining condition	**R_a (µm)**	**R_{max} (µm)**	**P (kW)**	**W (mm)**
F_L-N_D-N_P 70-30-6	0.76	7.07	2.065	0.395

Table 4- Results of the validation test

After validating the results of the optimization for MQL turning; additional experiments were performed under dry and wet conditions at the same cutting speed, feed and depth of cut to compare machinability in terms of tool flank wear, machined surface roughness and power consumption. An emulsion of water and mineral oil was used as the cutting fluid in wet cutting at a flow rate of 2 L/min. The results have revealed significantly lower values of tool flank wear and total power consumption for MQL compared to dry and wet conditions. The surface finish measured for MQL was much better than those of the dry condition, but a little less than that of the wet condition.
Table 5 presents the results of this comparative study which comprehensively confirms the advantages of MQL when compared to dry and wet cutting conditions during turning of Grade-4 titanium.

Machining condition	**R_a (µm)**	**R_{max} (µm)**	**P (kW)**	**W (mm)**
MQL	0.76	7.07	2.065	0.395
Dry	1.15	8.77	3.433	0.820
Wet	0.61	4.07	2.553	0.708

Table 5- Comparison of MQL, dry and wet machining

6 CONCLUSIONS

The results of the present work contribute to overall sustainability by achieving improved energy, resource and economic efficiency when machining Grade-4 titanium with the assistance of MQL. The following conclusions can be drawn from the present research work:

- Machining with the lowest MQL flow rate results in minimum roughness and power consumption, but for low tool wear machining with highest flow rate is best.
- Minimum roughness and power consumption are achieved at the lowest nozzle distance, whereas the low to midlevel distances provide lower tool wear.
- Machining with optimum parameters i.e. medium flow rate (70 mL/hr) and nozzle distance (30 mm), and high air pressure (6 bar) resulted in optimized work surface roughness, power consumption and tool wear.
- The comparative study comprehensively demonstrated the advantages of MQL over dry and wet cutting conditions when machining Grade-4 titanium.
- The difficulties usually associated with machining of titanium and its alloys can be significantly reduced by using MQL techniques.

The future scope of this work will include efforts towards optimization of work piece surface roughness, investigation on the effect of cutting speed, feed rate and depth of cut on the machinability of Grade-4 titanium especially as related to cutting forces and on the geometry (form features) of the machined part.

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8 BIOGRAPHY

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Investigating the Energy Efficiency and Surface Integrity when Machining Titanium Alloys

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Abstract

Sustainable manufacturing strategies will need to address the resource efficiency and surface quality challenges in cutting processes. This paper aims to provide a systematic methodology for modelling the input and outputs of a turning process to find the best balance between production rate and input cost, while improving or adhering to the quality standards. Ti6Al4V were cut under flood cooling using carbide cutting tools and a Taguchi design of experiments was used with ANOVA. Surface integrity and energy use were measured and analysed for selected cutting parameters. The experimental results highlighted the importance of selecting optimum cutting parameters and machining strategy. More energy was consumed at lower cutting parameters, whilst higher feed rates resulted in less energy consumption, but lower surface finish quality. These results will also assist to define the boundary conditions for various input parameters.

Keywords

Ti6Al4V, energy efficiency, surface integrity

1 INTRODUCTION

Industry is a major contributor to a nation's economic development and growth. In fulfilling this mandate manufacturing industries consume significant energy, often inefficiently, and as such are a major contributor of CO_2 emissions. There seem to be an inherent conflict between industrial energy efficiency and economic growth in rapidly industrialising economies. As such energy efficiency of production systems, especially machining operations, is becoming increasingly relevant and is a key element of consideration in most machining manufacturing operations [1]. Titanium alloys are gaining significant usage in aircraft structural and engine components, requiring excellent surface finish as the surface integrity of the components is critical due to the safety, reliability and sustainability concerns [8]. Ti6Al4V being a high strength material poses surface quality and energy consumption difficulties during machining.

Surface integrity is one of the most relevant parameters used for evaluating the quality of finish machined components especially when dealing with features made with the intention of attaining the highest level of reliability such as those used in the aircraft industry [2, 3].

Good surface quality is desirable for the proper functioning of most machined parts as well as meeting one of the most specific customer requirements. Surface Integrity (SI), therefore, refers to a broad range of surface quality characteristics encompassing the topography, mechanical, chemical and metallurgical state of a machined surface as well as its functional performance [4, 5, 6 and [7]. Most titanium aircraft structural components are finish-machined [8]. Surface roughness is the most used quality index for assessing the desirability of the machined parts in machining engineering [9]. Machining for the purpose of achieving the desirable surface integrity standard is energy intensive especially when dealing with high strength alloys such as Ti6Al4V. The main causes of surface alterations during material removal processes through machining are high thermal gradients, mechanical working in and beyond the limit of plastic deformation and chemical reactions and subsequent absorptions into the machined nascent surfaces [10, 11, 12 and 13].

The growing demand, and continued rise in the value of energy, serve to emphasise the importance of enhancing the energy and material-related efficiency of the Ti6Al4V alloy machining. Efficient energy management forms an integral part towards sustainable production systems [14] [15]. Optimising machining processes will also significantly help to address the sustainable manufacturing requirements set by various governing bodies. Efficient energy management also helps to enhance component surface quality acceptability, cut the operational costs of manufactured products and to reduce the ecological impact [16].

Energy efficiency during a machining operation gives prominence to the relationship between the amounts of energy resources deployed for a task as compared to the output achieved from the activity, [17]. It is important at this stage to establish the cutting parameters which will lead to the production of fit for purpose components with appropriate surface quality at the optimum level of energy consumption. Yet not many publications are available about this aspect. Optimising and predicting the energy usage in advance of the machining process would be important in enhancing cost effective machining. Reducing energy consumption through using optimum machining conditions contributes to sustainable manufacturing and this involves minimising material energy resources, [18].

Thus, the experimental study sought to establish the critical machining parameters (cutting speed and feed rate) required to minimising energy use and surface roughness during the turning of Ti6Al4V.

The model was used to establish optimum operating parameters. The energy consumed during a machining operation was segmented into different functional activities as an improvement on the previous research findings [19, 20, 21 and 22]. The machining energy refers to the energy required to remove the work-piece material under different process conditions. Broadly the required power for a given machine tool is composed of the constant and the variable components [19, 23]. The constant power component relate to the power assigned to the machine tool accessories such as the computer, pumps, fans and lighting. This power is not influenced by the machining parameter settings as the variable power is. Variable power depends on the process parameters [23].

The main purpose of this research study, therefore, is to experimentally investigate the interaction of the machining parameters (cutting speed and feed rate) for the purpose of systematically achieving optimal quality performance with regard to surface integrity of the work piece and energy consumption during the machining process. This is anticipated to greatly enhance machining processes unlike the current scenario whereby generally the desirable cutting parameters are determined based on the machine operator’s experience or by using handbooks that does not address sustainability. Furthermore ANOVA is done to see which process parameters are statistically significant. Thus, the ultimate goal is to optimise the machining process with regards to energy efficiency for the machining of the Ti6Al4V.

2 EXPERIMENTAL SETUP AND DESIGN

Turning experiments were performed on an Efamatic CNC lathe (model: RT-20 S, Max. spindle speed 6000 RPM). The sample material was Ti6Al4V (Grade 5) titanium alloy supplied in annealed condition at 36 HRC as a solid round bar (Ø=75.4 mm x 180 mm long). Figure 1 illustrates the various levels at which energy management can be performed in a manufacturing system.

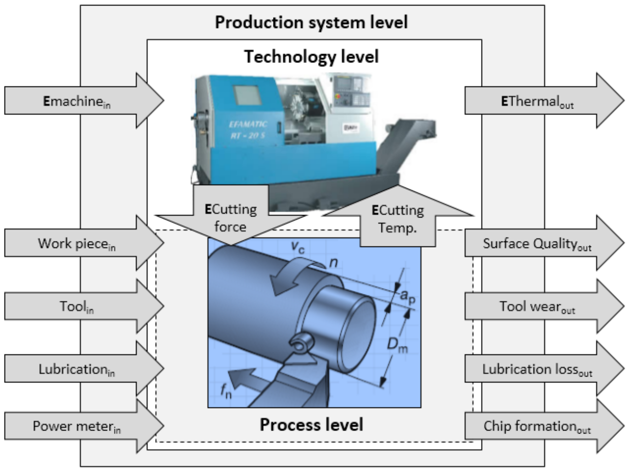

Figure 1 - The input and expected output at different levels of a machining operation that effects energy management [1, 14]

It also illustrates the input and output levels. The focus of this research study was the energy transformation stage at the machining process level. Electrical energy is supplied to the CNC lathe and is converted into mechanical energy (kinetic) which is used to separate the material during cutting at the different cutting speeds and feeds. Some of the energy is used to power the machine functional unit modules (as constant power) as well as to supplying lubrication and cooling at the cutting tool work piece interface. At process level during cutting the kinetic energy is transformed into various energy outputs. The experimental set-up is shown in Figure 2.

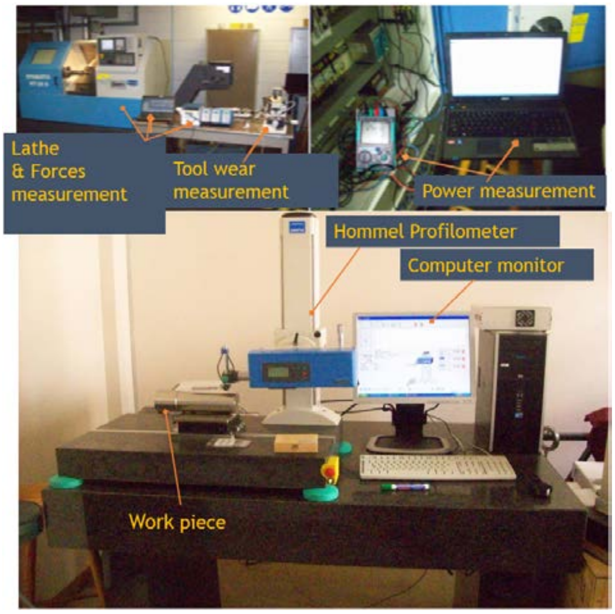

Figure 2 - Experimental setup of the machining experiment, the energy measurement system and the surface roughness measurement facility

A solid carbide tool (CNXMX 12 04 A2-SM, rhombic insert 80^{o}) in a Sandvik tool holder (DCLNL 2525 M12) was used for turning Ti6Al4V with conventional flood cooling. The cutting conditions were varied during the experimental process with cutting speed, v_c= 150- 250 m/min in steps of 50 m/min and f_n= 0.1-0.3 mm/rev in steps of 0.1 mm/rev. The depth of cut was kept constant at 0.5 mm. To conform with the ISO Standard 3685-1977 (E) for single point turning tools a wear criterion of V_B=300 µm [24] was used for all the machining experiments. Surface roughness (Ra) was measured using a Jenoptik Hommel Etamic T1000 profilometer connected to a computer with Hommel tester Turbo-Datawave software. Power measurements were taken using a KYORITSU ELECTRICAL MODEL 6300 3 phase digital power meter with the KEW POWER PLUS2 power signal recordings captured and read off an Acer Aspire 5551 Laptop running on Windows 7.

Taguchi L9 Orthogonal Array were used to plan the experiment matrix. This provides a set of well-balanced minimum experiments number which serves as an objective function for optimisation, i.e. the entire parameter space can be studied with a small number of experiments only. The levels of independent test parameters and the coding identification, as used on the experiments, are shown in Table 1.

			Coding of Factor Levels		
			Low	Centre	High
			-1	0	1
Cutting speed	v_c (X_1)	m/min	150	200	250
Feed rate	f_n (X_2)	mm/rev	0.1	0.2	0.3

Table 1 - Levels of independent test parameters and the coding identification

Significant process parameters are determined by using the statistical approach of Analysis of Variance (ANOVA) at the confidence level of 95%. This implies that an input parameter is considered to have significant influence on the response factor if its P value on the ANOVA is equal or less than 0.05. The experimental results are then transformed into the signal-to-noise (S/N) ratio in order to measure the quality characteristics deviating from the desired values. The objective function values are converted to S/N ratio in order to determine the performance characteristics of the levels of control factors against these factors. The three categories of the quality characteristics in the S/N ratio analysis are:

Smaller is better characteristic which is computed from the equation (1);

$$SN_S = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \quad (1)$$

nominal is best characteristic which is computed from equation (2);

$$SN_T = 10\,log\left[\frac{\bar{y}^2}{S^2}\right] \quad (2)$$

And larger is better which is computed from equation (3);

$$SN_B = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right] \quad (3)$$

Regardless of the category of the quality characteristic the optimum operating conditions are obtained by selecting the parameters that gives the maximum values of S/N ratio. This is done by using the main effects plots of the S/N ratios [25, 26, 27]. Joint consideration of the S/N and the ANOVA provides the prediction platform for the optimum combination of operating parameters.

3 RESULTS AND DISCUSSION

ANOVA results show that feed rate has a significant influence on surface finish. The P-value for cutting speed is insignificant at 0.074 which is above 0.05 the cut-off point of significance at 95% confidence interval. Thus variation of the feed rate will have significant effect on the quality of the surface finish on the work piece.

The experimental matrix and the results summary of the surface roughness and energy consumption are detailed on Table 2.

Experimental Plan		Response Parameters	
		Surface Roughness R_a [Microns]	Machining Energy [kJ]
150	0.1	0.200	332.595
150	0.2	0.633	175.001
150	0.3	1.167	122.113
200	0.1	0.267	235.356
200	0.2	0.867	132.912
200	0.3	1.467	96.020
250	0.1	0.233	190.650
250	0.2	0.767	106.025
250	0.3	1.600	59.193

Table 2 - Experimental Matrix and Results Summary

The Regression model depicting the mathematical relationship between cutting speed, feed rate and surface roughness is shown in equation (4).

Surface R_a = -0.778 + 0.002000 v_c + 5.889 f_n (4)

The coefficient of determination (r^2 value) of 96.53% depicts a good fit of the regression model to the underlining data.

Optimisation of the machining parameters for surface roughness is achieved by performing a Taguchi analysis of surface roughness considering the main effects plots of the signal-to-noise ratios. Figure 3 as well show that feed rate has prominent influence on the response parameter. Feed rate has the highest positive value on the main effects plots and it is ranked number one in terms of its influence on the surface roughness as shown on the response Tables extracted. The ranking shows that feed rate has the more pronounced effect on the surface roughness.

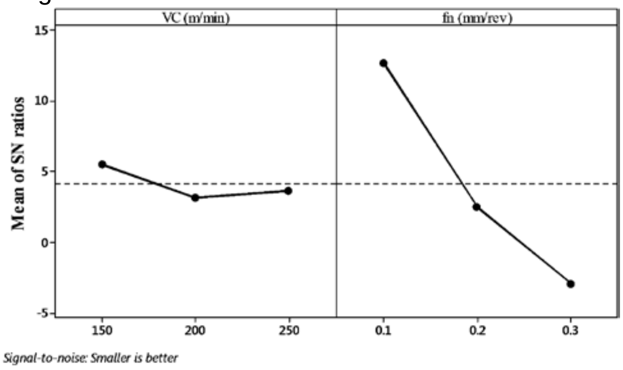

Figure 3 - Main Effects Plot for S/N Ratio on Data Means of Surface Roughness (Ra)

In terms of the statistical procedure of Signal-to-Noise assessment, the S/N response with the highest positive value presents the most optimum operating point. Noise factors cannot be controlled during processing, but during the planning [28]. Higher values of S/N ratio pin point control factor settings that minimise the effects of the noise factors. Thus accordingly the best optimal surface roughness of 0.2 microns is achievable when the machine parameters setting are at cutting speed of 150 m/min and feed rate set at 0.1 mm/rev. Figure 4 shows that as feed rate increases the surface roughness also increases, but the net cutting energy decreases. This arises due to the fact that as feed rate increases, the material removal rate also increases. Thus time is saved. The same trend is observed with the process total energy (Figure 5) where in as the feed rate increases the process energy required decreases due to the fact that less cutting time will be reduced

Analysis of variance of the material removal rate shows that both cutting speed and feed rate have significant influence on the MRR. It is apparent from the ANOVA that MRR is significantly influenced by both cutting speed and feed rate as their p – values are below the 0.05 value. The response shows that feed rate is ranked number one for influencing the material removal rate.

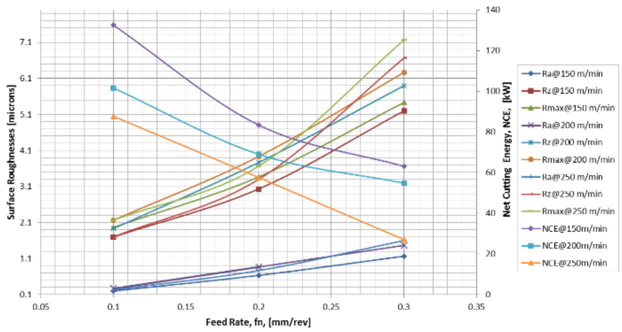

Figure 4 - Feed vs 3 Surface Roughness Types (R_a, R_z, R_{max}) vs Energy

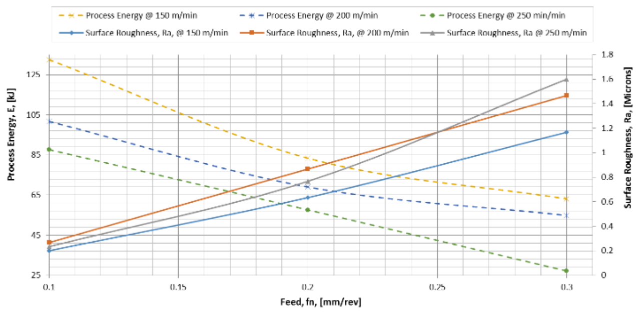

Figure 5 - Feed Rate vs Surface Roughness vs Process Energy

The Regression Equation relating the input factors to the response function (MRR) is given in equation 5:

MRR (mm^3/sec) = - 439.5 + 2.077 v_c + 1848 f_n (5)

The Optimising process parameters are obtained by considering the main effects plot (Figure 6) and the S/N ratio for energy shown on Table 3. The optimum condition for operating energy is 59.193 kJ achievable when operating at the cutting speed of 250 m/min and feed rate of 0.3 mm/rev.

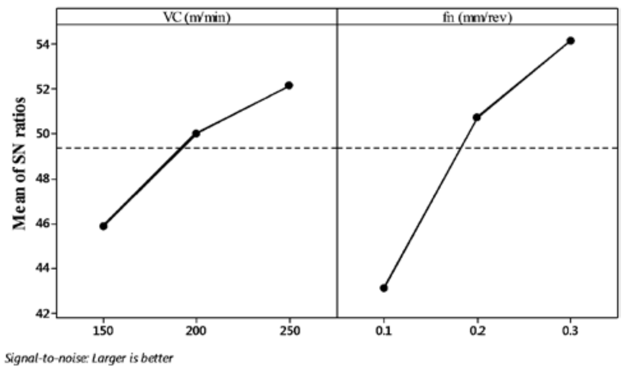

Figure 6 - Main Effects Plot for S/N Ratio on Data Means: Material Removal Rate (MRR)

Cutting Speed (m/min)	Feed Rate (mm/rev)	Total Energy (kJ)	SNRA2
150	0.1	332.595	-50.438
150	0.2	175.001	-44.861
150	0.3	122.113	-41.735
200	0.1	235.356	-47.435
200	0.2	132.912	-42.471
200	0.3	96.02	-39.647
250	0.1	190.65	-45.605
250	0.2	106.025	-40.508
250	0.3	59.193	-35.445

Table 3 - S/N ratio total energy

The MRR vs Machine total energy vs Efficiency graphical plot shown in Figure 8 shows that process energy use efficiency increases as the material removal rate increases and at the same stage when the machine energy use rate would also be decreasing respectively. This could be attributable to the reduced processing time when the feeding and cutting speeds are set high, ceteris paribus, the rate of material removal tends to be high. Thus the machining process efficiency keeps improving also.

4 CONCLUSION

The research set out to assess the energy efficiency and surface integrity of turning operations of Ti6Al4V titanium alloy. The machining experiments showed that feed rate has a higher significant effect on machined surface finish, but energy efficiency is influenced by both as they affect the rate of material removal. Optimum surface finish of 0.2 microns is achievable when the machine parameters setting are at cutting speed of 150 m/min and feed rate set at 0.1 mm/rev. Energy optimisation is attainable when operating at 250 m/min cutting speed and feed rate of 0.3 mm/rev given that MRR will be maximised. Regression models were deduced for the surface roughness and energy consumption. Thus, there is need to strike a balance between maximising MRR and reducing energy consumption as this provides the most optimum energy use rate during the machining.

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6 BIOGRAPHY

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Investigating the Feasibility to Remove Alpha Case from Titanium Alloys with Machining

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Abstract
Titanium as an alloy offers excellent material properties including corrosion resistance, biocompatibility and high specific strength. These properties make titanium alloys highly desirable in demanding applications and specialised industries such as aerospace and orthopaedic prosthesis. However, the formation of a hard and brittle alpha case layer at elevated temperatures requires hot forming processes to be conducted either in inert atmosphere, or vacuum. Alternatively, alpha case could be removed post process by chemical milling which requires high capital costs as well as stringent safety measures. Alternative removal techniques are therefore under investigation and one such option is machining removal which can make use of the already established South African machining industry. Excessive wear due to the hardened alpha case layer results in machining removal not currently being viewed as economically feasible. This investigation therefore focusses on identifying possible machining guidelines for the removal of alpha case from titanium alloys. Thereafter, a comparison is made between machining removal of alpha case with chemical milling in the context of the South African manufacturing industry. It was observed that alpha case is readily removed at all machining conditions and that excessive notching and accelerated wear rates are experienced at high cutting speeds. Wear rates more commonly attributed with titanium machining is observed at lower cutting speeds.

Keywords
Alpha case removal, Machining, Titanium

1 INTRODUCTION

At temperatures above 600°C, titanium experiences oxidation through interstitial diffusion where oxygen diffuses into the material substrate. This oxidation results in the formation of a thin, hard and brittle, oxygen enriched surface structure, of mainly alpha phase titanium. Oxidation changes the surface structure and composition, which strengthens and hardens the alloy [1]. Figure 1 illustrates the effect of heat treatment in ambient air on the hardness profile of titanium samples, and shows a two fold increase in hardness close to the edge.

The alpha case layer exhibits an increased Young's modulus (measure of stiffness) compared to the substrate, and the variation in stiffness across the surface of the material causes localised micro failures to form. Fatigue crack initiation areas form as part of the micro failures, compromising the integrity of the component, causing it to fail [3]. Alpha case also causes a significant loss of tensile strength and a reduction in fatigue performance [4]. It furthermore lowers the already low machinability of titanium alloys due to the increased hardness of the surface layer, which is why many titanium hot processes such as welding and melting are performed in vacuum or inert atmosphere [3]. Certain processes such as hot rolling can however not practically be performed in vacuum or inert atmosphere, and alpha case therefore has to be removed post process [5].

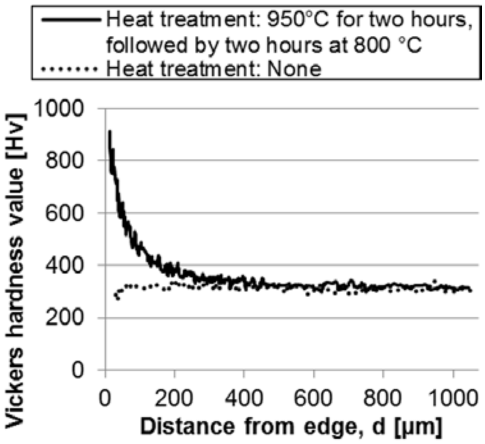

Figure 1 - Hardness depth profile comparison of heat treated and untreated titanium – adapted [2]

Current removal techniques most commonly comprise chemical milling in which the component is submerged into a heated acidic solution whereby aggressive acids etch away the surrounding alpha case. The chemical milling process is not complex but if not properly and safely executed can become hazardous, costly and wasteful in terms of workpiece material, and solution [6]. No chemical milling facilities capable of alpha case removal is currently available in South Africa, and the construction thereof would incur high start-up cost, stringent safety requirements, and extensive reprocessing and disposal cost of used acids. Alternative removal methods are therefore under investigation and one such method is machining removal.

This study aims to determine the possibility of using face milling with indexable tungsten carbide cutting tools as an alternative removal method of alpha case formed during hot rolling, in the context of the South African manufacturing industry. Additional advantages include that further semi finishing and finishing of components can be performed immediately after the removal of the surface layer, and that the safety risks associated with chemical milling will be mitigated. An economic study will also determine if the machining feasibility can translate into economic feasibility.

2 EXPERIMENTAL SETUP AND DESIGN

A wrought, grade five alpha beta alloy Ti6Al4V was be used for this investigation. A purely thermal heat treatment regime, illustrated in Figure 2, was implemented for the formation of alpha case which simulated similar conditions experienced during titanium hot rolling.

The cutting tool used in this investigation was a multifunctional face milling cutter incorporating double negative octagonal inserts. The tungsten carbide cobalt micro-grain cemented carbide cutting inserts are coated with a TiN and TiAlN multi-coat which is applied by physical vapour deposition.

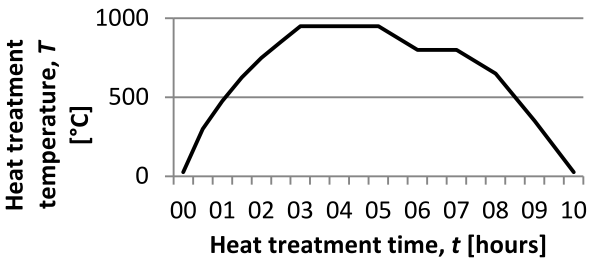

Figure 2 - Heat treatment cycle of titanium samples used for machining experiments

The effect of alpha case on the life of unused carbide cutting tools was investigated at various cutting parameters on a Hermle C40 U Dynamic 5-axis CNC milling machine. The recommended cutting parameters follow the accepted practice for titanium machining of using low cutting speeds in order to promote long tool life. Based on manufacturer recommendations, cutting speed (v_c) was varied between 40, 60 and 80 m/min and cutting feed (f_z) was varied between 0.1, 0.15 and 0.2 mm/z. Depth of cut (a_p) was constant at 1 mm for all machining trials. Down (climb) milling was utilised, causing chips to be formed from thick to thin. Straight line cuts were performed with a width of cut (a_e = 35 mm) equal to 70% of the cutter diameter (50 mm) and the length of cut (255 mm). The cutting speed, feed and cutter depths are listed in Table 1 below.

ISCAR SOF 45				
a_p [mm]	a_e [mm]	z *[inserts]*	f_z [mm/z]	v_c [m/min]
1	35	6	0.1	40
			0.1	60
			0.1	80
			0.15	40
			0.15	60
			0.15	80
			0.2	40
			0.2	60
			0.2	80

Table 1 - Cutting feed and speed combinations for machining experiments

For a satisfactory amount of data to be acquired, samples were machined and heat treated a number of times. Every single machining straight line cut at a specific combination of cutting speed and feed removed roughly 9 cm^2 of material. A total of 100 cm^3 of material were removed before experimentation was halted, unless tool failure criteria were met. Tool wear were measured and quantified via optical microscopy to determine tool failure after every single straight line cut and surface hardness measurements of the workpiece surface were taken to determine if all of the hardened alpha case is removed. Tool life failure is stipulated as average wear on the flank face of all six inserts equalling 350 μm.

3 RESULTS AND DISCUSSION

3.1 Confirmation of successful alpha case removal

Initial heat treatment results in the titanium sample to exhibit a darker red/brown colouration instead of the traditional titanium metallic grey. Flaking is also evident on the outermost surface which is due to the formation of TiO_2 and Al_2O_3 surface layers. This phenomenon is fully described by Du, Datta, Lewis and Burnell-Gray. After machining, the oxidised surface resulting from heat treatment is replaced with the more commonly found metallic colour with traditional wear marks. The newly machined surface is smooth due to the flat rake surface of the carbide insert, with surface roughness ranging from R_a = 0.3 – 1.2 μm, depending on the orientation of the measurement and the cutting conditions.

Apart from surface roughness measurements on the workpiece surface, additional surface hardness measurements were also recorded. This was performed on every machined surface before subsequent heat treatment to confirm the absence of alpha case from the titanium samples. The typical hardness of the specific titanium alloy (Ti6Al4V) used in this investigation is 349 HV. Control hardness measurements of the clean titanium sample before heat treatment and experimentation exhibited a surface hardness of 357 HV.

The surface hardness of newly machined surfaces in which alpha case was removed exhibit average hardness measurements of 336 HV. The average surface hardness values are close to the prescribed titanium surface hardness which indicates that the alpha case layer has been successfully removed for all machining conditions. The feasibility of using machining removal of alpha case from titanium alloys has therefore been confirmed, as the hardened alpha case layer is replaced with the softer titanium substrate. Although this is not a conclusive method for determining alpha case removal, it is satisfactory for most processes. Alpha case machining removal is only a pre-machining operation. Further roughing and finishing operations are still to take place in subsequent operations. Furthermore, the surface integrity of the newly machined surface is also irrelevant as additional machining processes are to be executed on the newly generated surface.

3.2 Tool life

The tool life data and the material removal recorded at various cutting conditions when performing alpha case machining removal from titanium alloy Ti6Al4V are given in Figure 3 below.

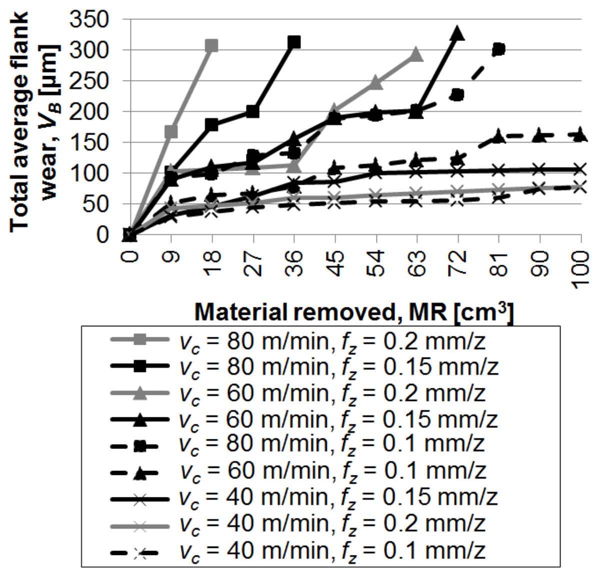

Figure 3 - Wear curves for different feed and speed combinations

As is common with titanium machining and machining in general, is that both the cutting speed and feed rate greatly influences the resulting tool life. The effect of feed rate is however dependent on the cutting speed. Lowering the feed rate from f_z = 0.2 mm/z to f_z = 0.1 mm/z at the highest cutting speed of v_c = 80 m/min, results in a 300% increase in total material removed by the carbide insert. Similar increase is experienced at cutting speed of v_c = 60 m/min, whereby a 200% increase in total material removal is experienced with a reduction in feed rate. However, at the lowest cutting speed of v_c = 40 m/min the effect of feed rate on the carbide wear is negligible as the total amount of material removed is identical for all three feed rates. Of the three different feed rates at cutting speed v_c = 40 m/min, only one (f_z = 0.15 mm/z) experiences slightly higher amounts of wear due to a large chip that formed during the machining trials. Disregarding the effect of the chip on the average tool wear of the remaining carbide inserts result in almost identical levels of wear across all three feed rates.

Different types of wear were recorded for different cutting parameters. At higher cutting speeds, the majority of the wear is restricted to the notch region. This is a special type of wear on the flank face that develops on the same height as the workpiece surface. In this case, it is the same region that contains the hardened alpha case layer. The alpha case layer is therefore directly responsible for the notching and the increased wear experienced by the carbide inert. Also common with this type of wear is that little or no wear is experienced below the notched region. This is illustrated in Figure 4.

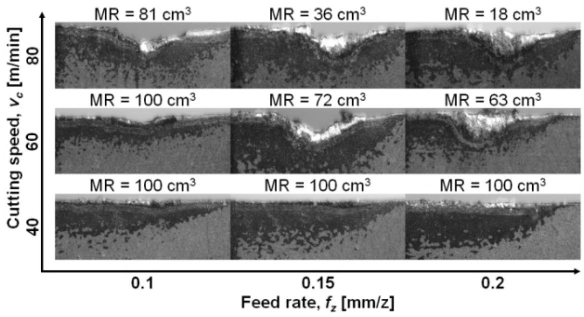

Figure 4 - Final tool wear observed on various cutting edges with the correlating cutting speed vc, cutting feed fz and total material removed MR

At lower cutting speeds, and lower material removal rates, the effect of the hardened alpha case layer is less prominent, and the notching effect experienced at higher cutting speeds is reduced. Gradual flank wear along the length of the cutting edge is experienced on most of the edges at low cutting speeds.

Maximum material removal was fixed to 100 cm^3, and four out of the nine possible machining conditions removed the prescribed amount before tool failure. The tool life for these cutting conditions is therefore not fully established. Furthermore, due to the large increase in wear experienced by some of the cutting tools when close to tool failure criteria, it was decided to declare a tool change slightly earlier than the prescribed amount (300 μm on the flank face). As a result, tool life is extrapolated to estimate total tool life for a total tool wear of 350 μm on the flank face. Linear extrapolation of the data yields total tool life and material removal exhibited in Figure 5.

The line graph represents the total cutting time, and the column bar represents the total amount of material removed. In terms of total cutting time, the more aggressive feed rates (f_z = 0.15 mm/z and f_z = 0.2 mm/z) result in very similar cutting times across all cutting speed ranges. Due to the excessive chipping experienced at the lowest cutting speed v_c = 40 m/min and f_z = 0.15 mm/z, total cutting time and total material removed is reduced. Disregarding the chipped insert from the average tool wear lowers the average tool wear which will consequently increase tool life. Furthermore the total amount of material removed for the particular cutting condition will more closely resemble the results of the other cutting conditions at v_c = 40 m/min.

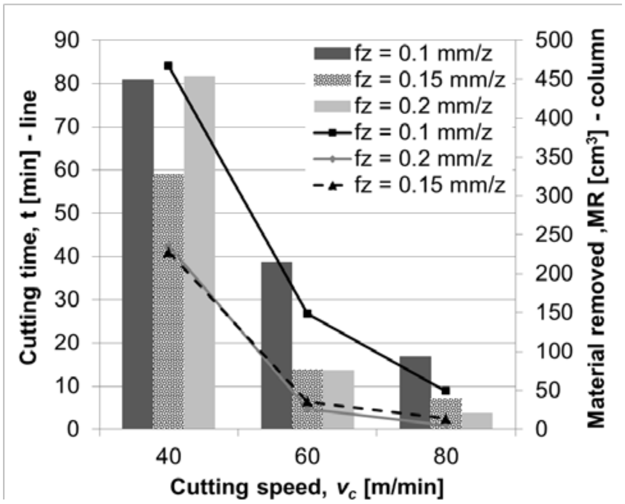

Figure 5 - Tool life projection curve based on extrapolated data observed in experiments

The column bars in Figure 5 illustrates the total material removed for all machining conditions and the shape of the column bars (total material removal) resembles the shape of the line curve (cutting time). At the lowest cutting speed (v_c = 40 m/min) two cutting conditions result in similarly high total material removal however at vastly different total cutting times. The higher material removal rate exhibited by utilising a higher feed rate of f_z = 0.2 mm/z, results in shorter cutting time for similar amount of material removal. This therefore increases the efficiency by removing similar amounts of material in a shorter amount of time. A more detailed analysis will however be required in order to determine the most efficient cutting condition.

Table 2 below illustrates the machining parameters that result in similar material removal rates across various cutting speeds and feeds. As this is a comparison of material removal rates, superior total material removal directly results in more cost effective machining. The least effective combination of speed and feed is at v_c = 60 m/min and f_z = 0.15 mm/z. Utilising a combination of elevated speed and elevated feed is therefore more damaging to tool life compared to high cutting speed and low cutting feed. However, utilising low cutting speed in combination with high cutting feed results in the most economical machining compared to the alternatives.

Feed rate, f_z [mm/z]	Cutting speed, v_c [m/min]	Material removal rate, MRR [cm^3/min]	Total tool life, t [min]	Total material removed, MR [cm^3]
0.1	**80**	10.70	8.8	93.7
0.15	**60**	12.03	6.4	77.0
0.2	**40**	10.70	42.4	453.7

Table 2 - Material removed for each machining speed and feed combination

4 COST MODEL

4.1 Milling Economics

Using the tool life data acquired during experimentation, total machine time and tooling cost can be estimated and an abbreviated unit cost curve similar to can be established. This will however only include the two most basic costs which will serve as an illustration for the basic costs of alpha case machining removal. Figure 6 above depicts the minimum unit cost curve for this investigation for each machining speed and feed combination.

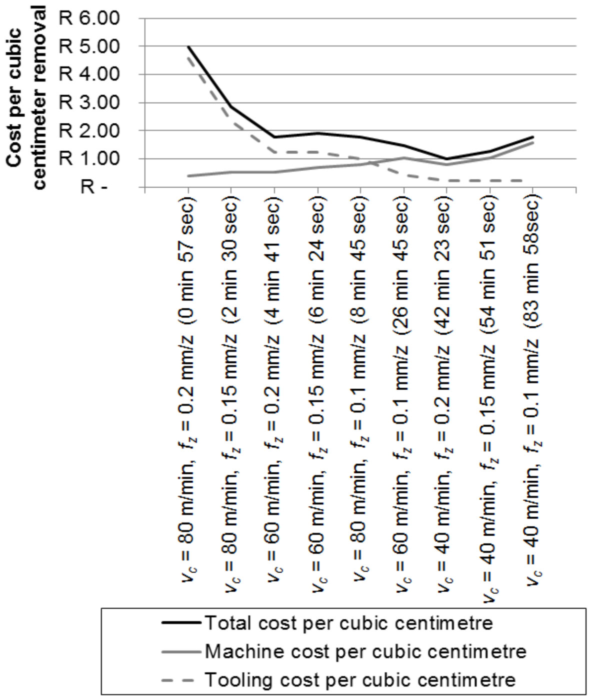

Figure 6 - Minimum cost curve for the removal of one cubic centimetre of material through milling

Cutting time is calculated based on the machining parameters and do not include setup and repositioning or internal tool travel, only actual machining time. The costs involved also only include machine and tooling cost for the removal of one cubic centimetre of material. The sum of the two costs results in the total cost of the removal of one cubic centimetre. The lowest cost of operation can be found at the lowest point in the cost curve. This position is located at a combination of using low cutting speed and high feed rate of v_c = 40 m/min and f_z = 0.2 mm/z.

The resulting unit which is most commonly used in the majority of studies that analyses the economics of milling is cost per cubic centimetre of material removed (ZAR/cm^3). This criterion is also used in this investigation to compare the economics of the different cutting parameters. However, the primary goal is not the removal of maximum volume, but the removal of maximum surface area. In other words, the goal is the clearance of alpha case from the largest possible surface area (cm^2). This investigation used a depth of cut of one millimetre for all machining experiments. This translates one cubic centimetre into ten square centimetres of surface area. Different depths of cut will result in different volumes of material removal; however the surface area will remain similar. As a result, the pre-machining alpha case removal operation can pre-machine titanium blocks closer to specified requirements before actual machining.

4.2 Break Even Analysis

The applicability of machining in the removal of alpha case from titanium comes down to feasibility. Both feasibility of removal, and economic feasibility. Feasibility of machining removal has been proven at low cutting speeds and high feed rates. The final question that needs to be addressed is; can the cost of machining realistically compete with the cost of chemical milling, and under what conditions in the context of the South African manufacturing industry. In order to come to a conclusion, the most economical machining conditions must be established, and the cost thereof should be compared to chemical milling.

In favour of machining removal is that machine shops are readily available in South Africa. With minor advances, titanium machining competency can be established. Supplementary equipment can also be acquired to further expand machining output. Such equipment can additionally be used for further finishing of titanium components, or be used for completely different tasks. The majority of the expenses associated with machining removal will be limited to consumables, labour and machine cost (variable cost). There is no requirement for high capital expenditure and start-up costs for new facilities and equipment (except for the acquisition of additional milling equipment). Furthermore, no training, safety equipment or additional safety requirements are necessary, and machining can start immediately as soon as the need arises using the prescribed guidelines. The costs of machining removal are therefore given in Figure 7 (a).

As there are no chemical milling facilities in South Africa, such facilities must first be constructed. Apart from the acquisition and construction of the facility; the equipment, safety measures and the practical skills required for chemical milling is not available in South Africa, and would need to be sourced from abroad. Additionally, extensive training will be required for new labourers with special emphasis on safety. The requirements listed above must first be obtained at high initial capital investment and will take a long period of time to fully be established. However, in favour of chemical milling is the low variable and maintenance cost. Once the facilities are up and running and a constant flow of projects are secured, chemical milling becomes a more economically viable option. The combination between the required capital investment and its variable cost is depicted in Figure 7 (b).

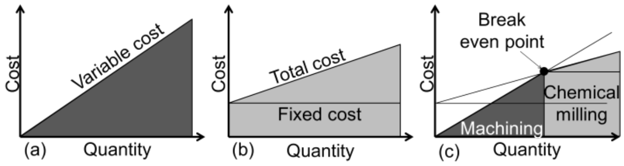

Figure 7 - Cost comparison of (a) machining removal, (b) chemical milling and (c) combined comparison of machining removal and chemical milling for small, medium and large theoretical quantities

Due to the costly nature of the initial capital investment required for chemical milling it is not deemed a viable option for low to medium quantities. Multi-purposing CNC milling machines to alpha case removal as well as final product machining is a more economical option overall. However, increasing the throughput of chemical milling would decrease the fixed cost per part of each individual component. This will ultimately lower the overall cost per part of chemical milling over the long term and increase profitability. In other words, at low- to medium quantities, machining remains the most economical option. However at medium to high quantities chemical milling could become more attractive financially. This break even schematic is shown in Figure 7 (c).

Chemical milling brings with it the use of highly acidic and dangerous acids which inherently increases the risk of using this removal method. Equipment and labourer safety must therefore at all times be the top priority. Acidic solutions must be properly stored in appropriate containers, and used solutions must be processed and disposed of in a manner that will endanger neither the operators nor the environment. Proper procedures should be in place in case of a chemical spill, and medical equipment and trained medical personnel must also be readily available should the need arise. Due to the nature of these risks, an extensive cost benefit analysis should be completed in order to determine if at a specific profitability, the risk of chemical milling not outweighs the benefit of the hazardous operation.

5 CONCLUSION

This paper determined the feasibility of alpha case removal from titanium alloys by method of machining, and the conditions which will allow this removal method to become economically feasible. Alpha case was successfully removed for all machining experiments. It was determined that at high cutting speeds the wear rates of the carbide cutting inserts are high and that unsatisfactory tool life is achieved. At lower cutting speeds however, tool life increased significantly and total material removal is similar to what is expected in traditional titanium machining operations. The removal of alpha case from heat treated titanium is therefore possible through machining, and the recommended machining parameters are high feed rates in combination with low cutting speeds.

Due to the high start-up costs and the stringent safety requirements, chemical milling is not deemed a viable option in South Africa for low production volume as the start-up cost will not be recuperated over the long term. Alpha case machining removal is therefore recommended using already established machine shops for low to medium production volume. Only at high production volumes will chemical milling be able to recuperate the high capital investment over the long term as the variable cost of machining removal becomes too high. The feasibility of machining removal is therefore possible in the South African manufacturing industry with low to medium production volumes.

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8 BIOGRAPHY

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Improving Part Qualifying Performance Using Compliance Crack Monitoring Under Rotating Bending Tests

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Abstract

Part qualifying testing is a critical part of product development especially for mission critical components. This is more pronounced in cases where new manufacturing techniques such as high speed machining, additive manufacturing and wire electrical discharge machining are applied. Such techniques invariably modify the surface integrity of the components by introducing amongst others residual stresses and altering surface roughness. If left unattended, this may affect the performance of the product in service. Therefore, there is a need to qualify products before full commercial production and to link the manufacturing strategy to anticipate in service part performance. Endurance qualifying tests for certain products and components may include full scale endurance testing and/or a machining strategy endurance evaluation by fatigue testing either axially or in bending. Crack growth monitoring can be used to indicate the durability and performance of the product. However, crack growth monitoring during axial or rotating bending conditions is challenging and expensive. The aim of this paper is, therefore, to report on the development of a compliance based crack monitoring technique that can reduce the cost and improve the effectiveness of product qualifying tests. Tests are conducted on grade 5 titanium alloy (Ti6Al4V) specimens produced using high speed turning. These are then subjected to a rotating four point bending configuration test. Defect (crack) formation and growth (size) may then be estimated by compliance (strain) monitoring. This technique was found to be a viable low cost option for monitoring components during rotating bending conditions and to link the manufacturing technique to part performance with specific reference to dynamic loading.

Keywords

Compliance monitoring, Part qualifying tests, Rotating bending fatigue tests, Surface integrity

1 INTRODUCTION

Mechanical products and other technical products in general, experience a wide range of mechanical stresses during production, transportation and service. In addition, they are subjected to a variety of environments during their life cycles which may extend or shorten product life. Some of these conditions cannot be predicted during product development and hence have to be verified by testing. Furthermore, manufacturing techniques are always evolving as new methods are developed mainly aimed at reducing product cost. A case in point is the introduction of high speed machining in the production of titanium components which may result in reduction of secondary processing costs. However, such techniques may have unintended consequences on product performance by introducing, among others, residual stresses and altering the surface roughness of the component [1], [2].

In the aerospace and automotive industries, more so for military applications, proving and certification tests are a necessity and stringent. For example military standards require certain levels of ruggedness which is qualified under a range of demanding conditions [3]. The same applies to civilian applications [4]. Therefore, Original Equipment Manufacturers (OEM's) have to conduct extensive product qualifying tests to comply [5]. This calls for low cost qualifying solutions to keep product development costs viable.

Most damage in critical mechanical components is due to alternating loads and hence stresses. This damage progresses through crack initiation and propagation leading to fracture. This commonly occurs at stress hotspot locations that typically exist on the surface of the component especially in components subjected to bending loads. Hence, this phenomenon determines the life of the component or product (fatigue). Fatigue tests are therefore a significant part of product development, product qualification and durability assessment.

Four and three point rotating bending tests including rotating cantilever tests are well established fatigue testing procedures for establishing the performance of rotating components such as rolling stock and automotive axles [6]. Crack growth monitoring, which is important to establish the extent of component damage and residual life, is difficult to implement under these conditions. Development of damage tolerance maintenance regimes relies on the ability to detect and monitor crack initiation and propagation. Therefore, this paper reports on a low cost methodology with potential to detect and monitor cracks during rotating bending fatigue testing which is suitable for application in qualifying product components subjected to rotating bending.

2 EXPERIMENTAL PROGRAMME

2.1 Aim

The aim of this experimental programme was to assess the fatigue performance of a selected machining strategy by measuring the variation of surface strain on a specimen during four point rotating bending fatigue testing.

2.2 Materials

Tests were conducted on specimen machined from grade 5 titanium alloy (Ti6Al4V), extra low interstitial (ELI) alloy supplied in bars of 31.55 mm diameter and length of 152.4 mm. According to the material certificate, the composition of the material was 0.008% nitrogen, 0.013% carbon, 0.0021% hydrogen, 0.18% iron, 0.12% oxygen, 6.03% aluminium, 3.94% vanadium and the balance being titanium. The material met the ASTM F136 specifications. Nominal mechanical properties according to the material certificate are given in Table 1.

Ultimate Strength (MPa)	0.2% Proof Stress (MPa)	Elastic Modulus (GPa)	Hardness (HRC)	Elongation (%)
1026.6	939.3	115	32	14

Table 1- Material properties of Grade 5 titanium alloy.

2.3 Specimen Preparation

2.3.1 Specimen Geometry

A range of different specimens are suggested for rotating bending fatigue testing. The configuration for the specimen used in this investigation is shown in Figure 1. This geometry is also recommended by ASTM E466-96(2002) and the DIN 50113 standards. It was selected based on the need to capture the effect of high speed turning over a representative size of the specimen surface. The gauge length of 50 mm provides an effective turning cut length of 12.57 m that allows this to be achieved. The specimen diameter of 16 mm was dictated by the need to attain 250 m/min for the available maximum machine spindle speed of 6000 rpm.

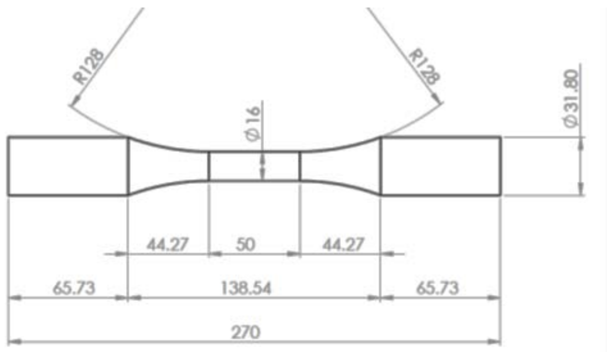


Figure 1 - Rotating bending fatigue specimen

2.3.2 Specimen Manufacture

Specimen were manufactured by turning using a range of cutting speeds. Machining speeds of 70 m/min, 150 m/min and 200 m/min were selected to investigate the effect of HSM on fatigue performance of Ti6Al4V. These cutting speeds corresponded to spindle speeds of 1392.3 rpm, 2984.2 rpm and 3978.9 rpm respectively. Accelerated tool wear and spontaneous ignition of chips limited the cutting speed to 200 m/min for both dry cutting and conventional flood cooling. The depth of cut was set at 0.25 mm with a feed rate of 0.2 mm/rev under flood cooling. This represents typical finishing cut machining conditions. This also captures the typical conditions under which machined components are placed into service. A total of 10 specimens were prepared at each of the selected cutting speeds.

The cutting tools used were supplied by Sandvik Coromat. The recommended tools for cutting titanium are H1P and H13A. These are both supplied with and without chip breaking technology. An uncoated cemented carbide tool insert (H13A) with a tool nose radius of 0.8 mm and chip breaking technology was used for this investigation. The exact designation of the tool used is:

DNMG 15 06 08 – 23 H13A

where D represents 55^o included angle tool shape, N is the 0^o insert angle, M is the tolerance, G is the chip breaker shape, 15 is the tool cutting edge length in mm, 06 is the insert thickness in mm, 08 represents the 0.8 mm tool nose radius and 23 is a manufacturer geometry code, in this case indicating finishing cutting.

2.4 Equipment

Specimen machining was conducted on a high speed Efamatic RT-20 S CNC lathe machine running a FANUC controller (Figure 2). This is a single spindle machine with a maximum spindle speed of 6000 rpm driven by a 15 kW hydraulic motor. The AC servo motor driven x- and z-axes travel at 24m/min with a maximum radius of 260 mm for the x-axis and 450 mm for the z-axis. The machine is equipped with a quick indexing 12 post tool turret with integrated high pressure coolant delivery system. All specimens were prepared using the same machine which ensures that variables of machine stiffness remain constant.

Figure 2 - Efamatic RT-20 S CNC machine

Specimen were subjected to rotating bending fatigue to initiate defect formation. A special rotating bending fatigue testing machine was developed for this purpose to achieve the required load levels. The machine developed is shown in Figure 3.

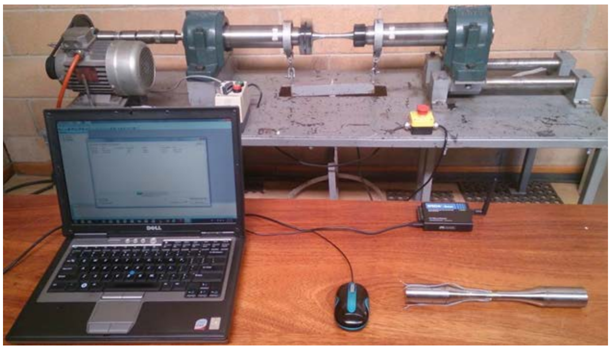


Figure 3 - Rotating bending fatigue testing machine

2.5 Experimental Procedure

Prior to testing, the fatigue machine was calibrated by loading the specimen while monitoring strains under static conditions. To monitor crack initiation and growth, strain gauges were mounted onto the specimen as shown in Figure 4. Strain logging was done using wireless strain loggers (SG Link) supplied by Microstrain. These allow real-time wireless transmission of the strains to a base station connected to a data logging computer. Two strain gauges were used connected in quarter bridge configuration. System control was achieved using Node Commander Software supplied by Microstrain.

Figure 4 - Strain logging configuration

Calibration data obtained for the machine is shown Figure 5. The difference in loading and unloading data points is due to frictonal effects in the system. Since there was not return spring mechanism, the specimen remained loaded by displaced machine components leading to higher unloading strains. Furthermore, Figure 5 shows the relationship between the experimentally measured strains and the numerical predictions. The close correlationship validates the numerical model.

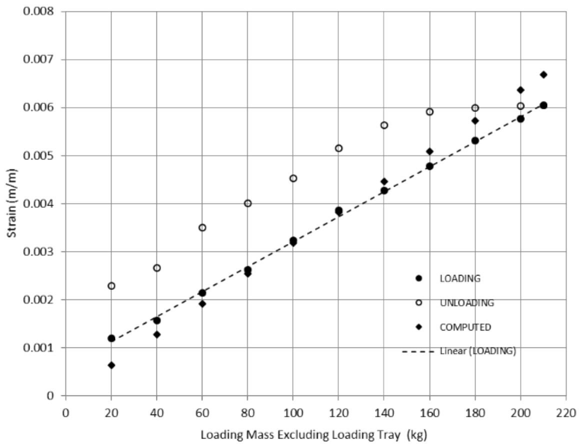


Figure 5 - Mass vs strain response of machine

3 NUMERICAL MODEL

3.1 Introduction

Numerical simulations in this work were conducted using the general Finite Element Analysis (FEA) package Abaqus 6.13 [7]. Abaqus provided two approaches to model cracked components. One approach is to model the crack geometry as accurately as possible by using extensive localised mesh refinement in the crack tip zone to capture the large stress gradients. This is implemented in Abaqus using the seam approach. This is a time consuming process both in terms of pre-processing, processing and post-processing but yields more information on the crack tip stress field. An alternative approach is the crack enrichment technique. In this case the crack is modelled as an enrichment feature without the need to refine the mesh in the crack tip zone in order to capture stress gradients. This technique is implemented in Abaqus 6.13 as extended finite element method (XFEM). XFEM was selected for crack size - strain calibration simulations due to its limited complexity and lower processing resources for non-propagating cracks.

3.2 Material Model

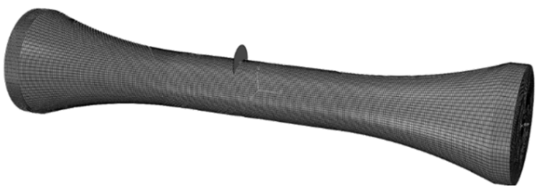
The material was modelled using a modified Jonson-Cook model to capture nonlinear behaviour [8]. The parameter modifications were made to match available material properties data. The parameters used are shown in Table 2 against the Johnson-Cook standard parameters.

Parameter	A (MPa)	B (MPa)	n	C	m
Current work	*939.39*	*461.09*	*0.34*	*0.012*	*0.8*
Johnson-Cook	862	331	0.34	0.012	0.8

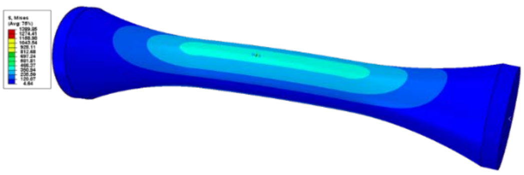
Table 2 - Johnson-Cook material parameters [8]

3.3 Model Geometry

The specimen was modelled as a 3D body built-in at one end and subjected to a point moment at the free end of magnitude 150 000 N-mm. The extended clamping sections on the two ends of the specimen were removed to reduce element count. After a mesh sensitivity study, an element size of 0.5 mm was selected. The initial crack was modelled as a circular disk of 1 mm diameter. Although there was an option to activate crack propagation, all cracks were considered stationary. Figure 5 shows the meshed specimen (a) and stress distribution (b). The uniformity of the stress distribution over the gauge length of the specimen is evident providing for the random crack initiation at any point along the gauge section of the specimen.



(a)



(b)

Figure 5 - Specimen model (a) Meshed (b) Stress distribution

3.4 Strain Response with Crack Growth

The crack size was varied in 0.5 mm increments of radius from 0.5 mm to 10 mm. In addition, the position of the crack was varied in increments of 5 mm from the centre of the specimen. The variation of strain with circumferential position for a crack located 5 mm from the centre of the specimen is shown in Figure 6.

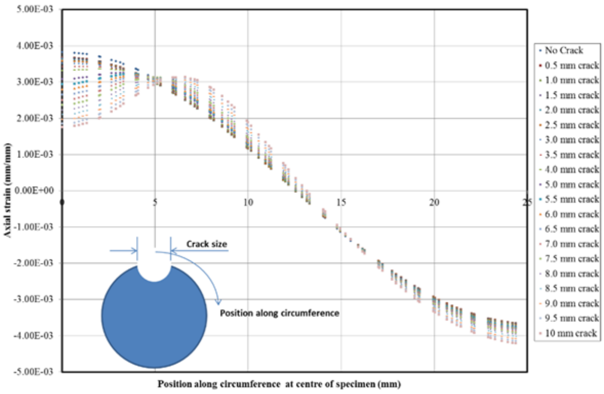


Figure 6 - Variation of strain with circumferential position for crack located 5 mm from the centre

When the deviation of the strain from the uncrack specimen response is considered, the strain distribution is shown in Figure 7.

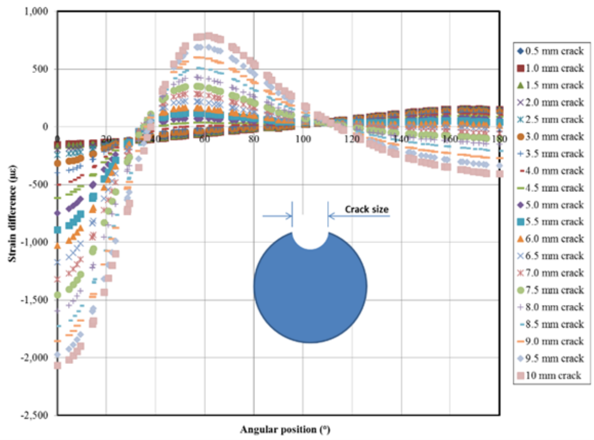


Figure 7 - Strain variation as a function of position along the circumference for different defect sizes (5 mm off centred in gauge length)

If the variation of the strain is now considered for a single location, the result is the response shown in Figure 8. This shows that as the crack propagates, the strain increases thus providing a means to monitor crack growth.

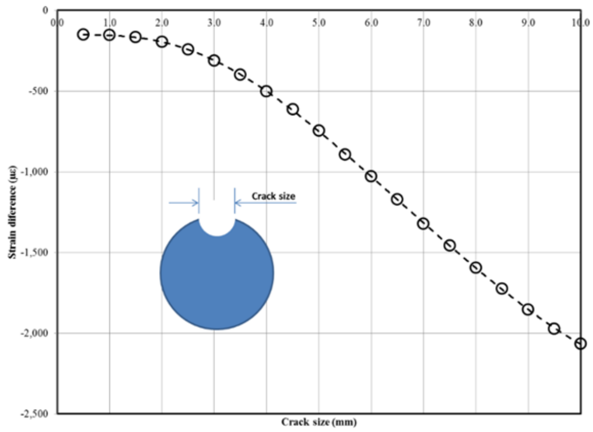


Figure 8 - Variation of strain at single point in line with crack initiation point as a function of crack size

4 FATIGUE TEST RESULTS

Figure 9 shows the fatigue signal for a titanium specimen subjected to a load of 160 kg (equivalent to 585.49 MPa on the gauge section). This represents 62.33 % of the yield strength of the material. This ensured a finite fatigue life since endurance limit for Ti6Al4V has been reported to lie in the range 529-566 MPa. The specimen failed after 51444 cycles. Data logging was conducted continuously at 128 Hz while the machine was running at 10 Hz. The figure also shows the expected change in strain as the specimen cracks and crack propagation progresses. This variation of strain (change in compliance) therefore provides opportunity to monitor crack growth during rotating bending tests. As expected, the crack initiation occupied a significant portion of fatigue life.

The quality of the signal is important to the success of this technique. For the current tests, no signal conditioning was applied.

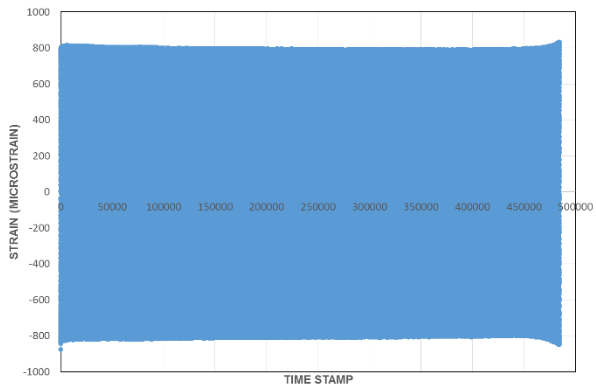


Figure 9 - Sample strain-time response during tests

The quality of the signal as obtained can be seen in an extract of a portion of the signal presented in Figure 10. Overall, the signals received were largely noise free. Minor errors occurred when resolving the peaks (turning points) because of the sampling rate that may not capture the exact maximum and minimum values. This was deemed insignificant when considering the total number of cycles evaluated.

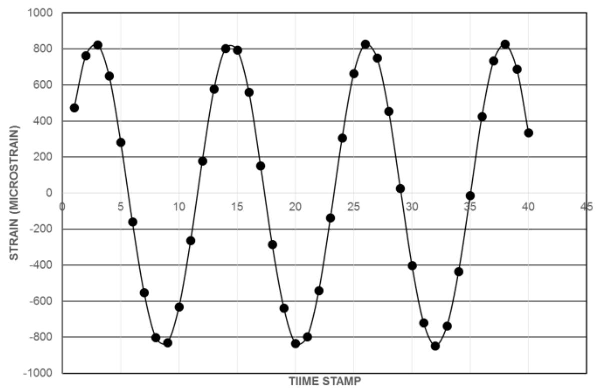
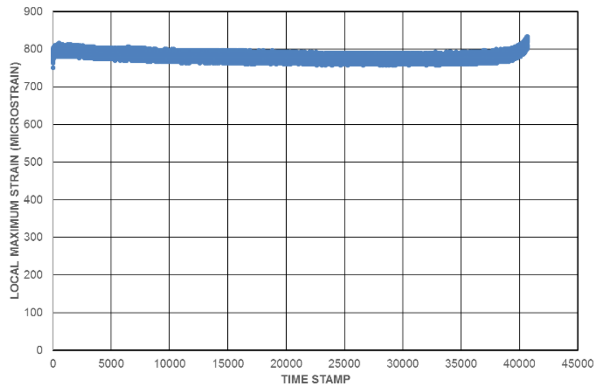
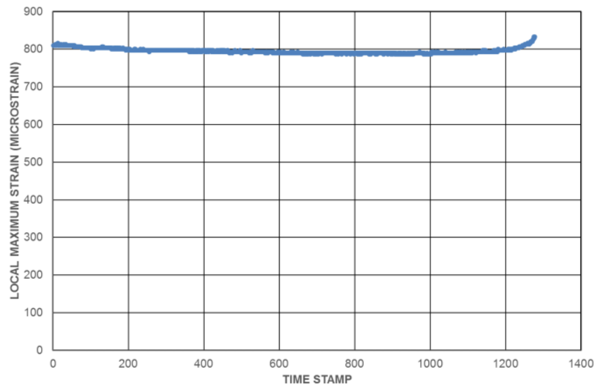


Figure 10 - Extract of the fatigue strain signal

To extract the crack growth information, the local maxima (positive) or local minima (negative) can be extracted. For this work, this was done by writing a simple analysis program in Matlab. Another simple tool that can be used is the VBA macros in Microsoft Excel. Data reduction in this case implies sequential maxima extraction. Simple averaging or filtering of the extracted maxima and minima values is inappropriate as it guarantees lower offset results. The result of the first maximum data point extraction run is presented in Figure 11(a). The result of a subsequent second extraction using the results of the first run as input data is presented in Figure 11(b). The banded nature of the signal in both figures shows the presence of secondary higher frequencies. These higher frequency signals could be caused by a variety of factors such as power transmission components (e.g. bearings and universal joints) or out of balance forces arising from strain loggers that were strapped to the collets. Spectral analysis will reveal more information.



(a)



(b)

Figure 11 – Maximum strains vs time

Further simplification of the local maximum strain signal yields the result shown in Figure 12.

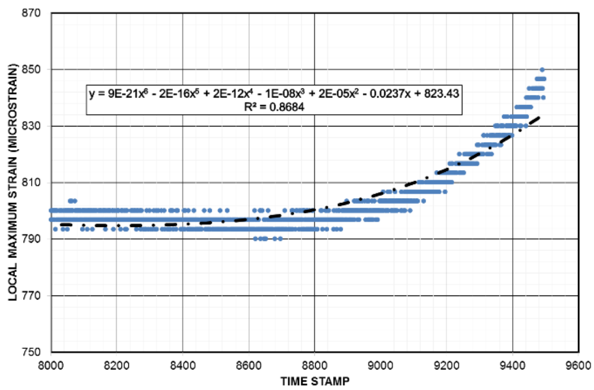


Figure 12 – Strain variation during crack growth

This variation in strain can therefore be used to track the progress of crack growth. The variation of the strain measured (change in compliance) at a known location is related to the size of the defect before final fracture occurs. When compared with the results of the finite element simulation the crack growth rate may be tracked. The fracture surface of the specimen is presented in Figure 13 at a magnification of 0.7. The image shows that this specimen failed due to the initiation and growth of a single crack as evidenced by the smooth surface. The beach marks towards the point of fast fracture suggest a change in rate of crack growth, possibly linked to the increased local stress levels due to decreased loaded area.

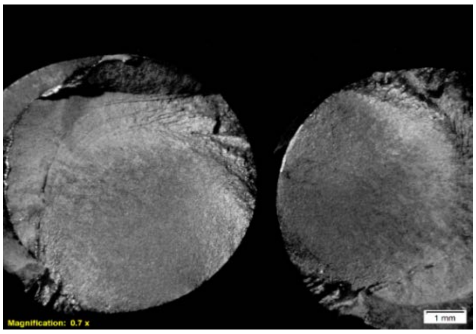


Figure 12 – Strain variation during crack growth

Furthermore, it can be deduced that stable crack growth consumed almost two thirds of the section. For a specimen of 16 mm gauge diameter, this represents close to 10 mm penetration. However, the oval nature of the stable crack growth area poses complications in relating the simulation to actual crack growth.

From Figure 12, the local strain close to the point of fast fracture is 850 micro strain. The deviation of this strain from the uncracked specimen is 2979.7 micro strain. From Figure 7, this corresponds to a crack radius of 11.5 mm which corresponds to a crack diameter of 23 mm. The actual measured penetration of the crack prior to fast fracture was found to be 10.3 mm from the surface. This gives an error of 11.65% according to simulation prediction. This is acceptable for practical engineering applications.

5 CONCLUSIONS AND RECOMMENDATIONS

In this paper, the crack behaviour during the rotating bending fatigue testing of grade 5 titanium alloy was studied using both numerical and experimental techniques. The crack behaviour was modelled using XFEM tool implemented in commercial FEM software Abaqus 6.13 while the strains were monitoring on the rotating specimen using strain gauges.

Based on the results obtained, the following can be concluded:

1. The tool that was developed can be used to monitor crack growth during rotating bending fatigue tests.
2. The tool is not sensitive enough to detect the onset of crack initiation
3. A crack with a penetration of 10.3 mm can be detected with an accuracy of 11.65 % on crack penetration

Further work is required to further refine the technique through more tests and the use of higher resolution strain measurements which can be achieved using fibre optics. This method can also be tested on other materials such as steel.

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7 BIOGRAPHY

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Fast and Reliable Quality Inspection of Micro Parts

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Abstract
A continuous trend to function integration, miniaturization and densification opens new opportunities in industry and research. Tools, materials and technologies have to be scaled down from the macro to the micro domain in order to manufacture micro products fast and reliable. Thereby, the downscaling of classical processes leads to unexpected process behavior, so called size effects, which show high variance due to a high number of influence factors. Based on these findings we introduce a novel setup for achieving fast automated optical control of micro parts using a light field camera (LFC), for additional depth of field as well as depth information. Information provided by the LFC is then used to automatically sort out fault parts after extracting a suitable set of features. The presented setup allows fast and completely automated 100% quality inspection of micro parts by use of different defect classes and inspection characteristics.

Keywords
Micro Forming, Quality Control, Metrology, plenoptic camera, light field camera

1 INTRODUCTION

The continuous trend towards the production of micro-products, -tools and –materials, i.e. with at least 2 dimensions below one 1 mm, also facilitates increasing demands regarding their functionality and the complexity of their geometries. One of the most promising solutions when it comes to metallic micro parts is micro metal forming. Especially cold forming procedures are not only marked by their high throughput with low energy and material expenditure, but also allow for designing complex production systems [1] [2]. However, the application of known processes from the macro- to the micro domain is often not straightforward as unexpected process behavior might occur, so called size effects [3]. For instance, scaling down the size of an object increases the amount of surface area in relation to the objects volume which causes a much more prevalent influence on adhesive forces. The resulting "stickiness" makes the handling of micro parts much more challenging. These effects are not limited to the production but also affect the quality inspection of micro parts. Small part dimensions require the use of precise measurement techniques, but the established tactile and microscopic techniques both are lacking in terms of measurement speed and applicability for inline quality inspection. Therefore in many industrial applications experts draw and inspect samples through a microscope in an offline way with manual handling. In safety-relevant areas, as in the automobile industry, it is however necessary to realize a 100% quality inspection to meet the safety and quality standards.

Here we present an approach for the 100% quality inspection of micro parts, so called micro cups, developed in the context of the Collaborative Research Center 747 – "Micro Cold Forming". Micro cups are manufactured using a micro blanking and deep drawing procedure developed at the Bremen Institute for Applied Beam Technology (BIAS) [4]. We first discuss common defects occurring during this process and then present a demonstration platform that is able to automatically detect three of the most common defect classes (bottom tears, wrinkles and unequal wall height) capturing only a single image by employing a light field camera.

2 PRODUCTION OF MICRO CUPS

2.1 Micro blanking and deep drawing

A combined micro blanking and deep drawing process is used to produce the micro cups measured in this work. The process achieves a stroke rate of 200 strokes per minute, by using a follow-on tool where the circular blank is positioned automatically. The steps for producing a micro cup are shown in Figure 1. After feeding (step 1) the metal stripe (50 µm thickness), it is held between the blank holder and the tool combination guide (step 2). During the blanking operation in step 3 the circular blank is cut out from the metal stripe and moved upwards to the deep drawing blank holder. In step 4 the cup is produced via deep drawing the circular blank through the hollow blanking and deep drawing tool combination by moving the punch downwards. The process starts again at step 1. The follow-on tool runs position controlled on a highly dynamic forming machine engineered at BIAS [1].

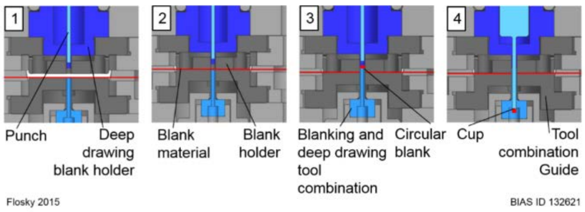

Figure 1 - Process steps for producing micro cups

Figure 2 (left), illustrates the micro cup production schematically. The press moves the follow-on tool and the metal strip is fed through the process by a feed system (Zehnder und Sommer EDV 040 - 220 DG).

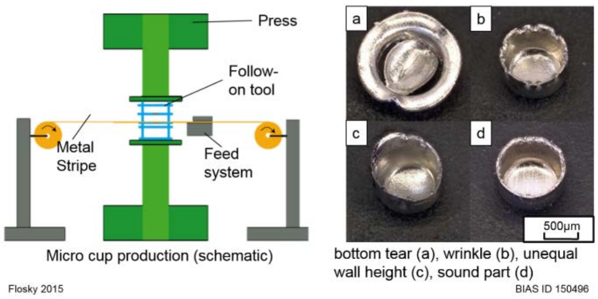

Figure 2 - Schematic of micro cup production (left) [2] and possible failures (bottom tear, wrinkle and unequal wall height) and sound part occurring in micro cup production [3]

2.2 Typical defects and causes

On the right side of figure 2 three failures are depicted which can occur in micro deep drawing: wrinkles, unequal wall height and bottom tears. Wrinkles occur if the blank holder force, which holds the circular blank between the (deep drawing) blank holder and the deep drawing die, in this case the blanking and deep drawing tool combination, is too low. On the other hand, if the blank holder force is too high, the circular blank is clamped too strong in between die and blank holder and bottom tears occur. The deep drawing punch goes through the circular blank as in a blanking process. As the process is position controlled, between blank holder and die is a just a 50 µm gap for the circular blank. If the punch goes through the metal stripe and causes a bottom tear, the bottom tear is still on the die (blanking and deep drawing tool combination) and after the next blanking step the bottom tear (50 µm) and the new circular blank (50 µm) are both between die and blank holder, where the gap is only 50 µm. This causes more and more bottom tears and the process forces are increasing until the process stops. Bottom tears can occur for one or a combination of the following reasons:

- anisotropic strip material behavior because of size effects [3]
- lubrication
- flake formation [4]
- tool wear

In micro metal forming, the thickness of the strip material is only a few micrometer, in this case 50 µm. The grain size of e.g. 50 µm Al99.5 strip material is up to 50 µm [5] and each grain has a preferred direction where the grain can withstand a higher tension than in other directions. If the orientation of the grain on the bottom corner of the micro cup is weak the possibility of a bottom tear rises. Another aspect of the strip material is a scattering in the thickness: if the strip material is thinner than 50 µm, wrinkles can occur while much thicker strip material leads to the appearance of bottom tears.

During the process presented here, lubricants are still necessary to e.g. reduce friction. However, if the lubrication of the circular blank is not constant the friction reduction on one side is higher than on the other and bottom tears can occur or a micro cup with irregular side walls.

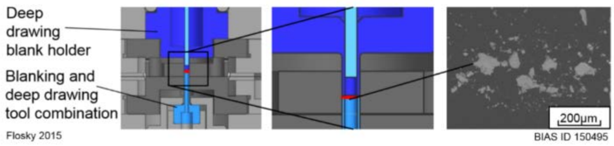

Figure 3 - Small metal parts out of the strip material (flakes) influence the process [2]

Lubricant has another function as it is cleaning the tool during the process. As shown in Figure 3 during the blanking process small parts (flakes) can break out of the strip material and can stick on the die (blanking and deep drawing tool combination). As mentioned before, the gap between die and blank holder is 50 µm and if circular blank and flake are in between the blank holder the resulting force is too high and a bottom tear occurs.

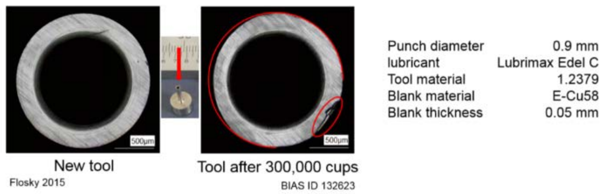

Figure 4 - Comparison between a new tool and a tool after producing 300,000 micro cups [2]

During the blanking and deep drawing process, tool wear by e.g. adhesive wear and edge disruption occurs [6]. An example is shown in figure 4 with the top view of a new tool (left) and a worn tool after 300,000 cups (right) of the blanking and deep drawing tool combination (middle). The diameter decreases and there is an edge disruption, which causes a smaller surface compared to the new tool. During the whole process, the same gap respectively blank holder force is loaded. By decreasing the surface the initialized pressure is increasing and the possibility of bottom tear rises.

3 QUALITY INSPECTION OF MICRO PARTS

3.1 Problems

There are multiple measurement techniques which are suitable for reliable dimensional metrology in the micro domain in terms of accuracy [5], like i.e. tactile methods [6], scanning electron microscopy (SEM) [7] or confocal laser microscopy (CLM) [8]. However, while they provide the necessary low measurement uncertainty, most these technologies are not suitable for in-process measurement. This can be due to special demands on micro part handling, an issue especially regarding tactile methods as they require contact with the measured part. Due to the large adhesive forces of micro parts this can make it necessary to lock the part in position, increasing both the demands on handling as well as the risk for damaging the part [6]. Nevertheless, difficult handling is not limited to tactile methods. SEM for example requires the measured part to be in a vacuum, which is hard to realize in-process [7]. A promising solution in this regard is CLM. It allows for high resolution 2D texture and 3D form analysis based on CLM with a measurement of time of ~30s [8]. However there is a problem for all of these techniques: low measurement speed. For in-process 100 % quality inspection it is necessary to inspect hundreds of parts per minute. It is hence necessary to employ a measurement technique that is able to acquire fast 2D and 3D information, while still providing enough accuracy to identify common defects in micro cup production. A possible solution to this problem is the use of a light field camera [9].

3.2 Light field technology for fast 2D/3D image acquisition

A Light field camera is a camera that uses the plenoptic principle [10]. By making use of an additional micro lense array the light field camera is able to calculate the light field, i.e. the direction of the incoming light. The light field contains information about different focus depth, providing additional depth of field, and can also be used to reconstruct a depth image. The Raytrix R5µ used in this work uses an enhanced version of this principle [11]. With 5x magnification it is therefore possible to capture a nearly completely sharp image of a micro cup with a single recording. In combination with the depth image it is hence possible to identify all of the aforementioned defects typical for micro cup production. The light field camera provides a conventional 2D image as well as an additional depth image which are saved in Bitmap format and then transformed into feature vectors using python and OpenCV.

3.3 Demonstration platform

To realize automatic quality inspection the light field camera was integrated into a demonstrator platform.

Because of size effects, the handling of micro parts poses its own challenges and requires the use of suitable tools. Due to the increased ratio of surface area to volume when scaling down the size of an object, micro parts are subject to larger adhesive forces, which increase their tendency to stick on surfaces. Consequently micro parts also tend to accumulate, which poses a problem for measurement and sorting out defective parts.

To counteract this tendency micro cups are first brought bulk-wise into a vibrating spiral conveyor (AViTEQ TFH 600) using a KUKA youbot robot arm. The vibration as well as additional barrier elements placed into the spiral conveyor counteract the accumulation of parts. Micro cups are then transported onto a conveyor belt where they are aligned in width direction by a guiding element. The guiding element is made out of Polyoxymethylen (POM) to avoid disturbances due to build-up of electrostatic charge.

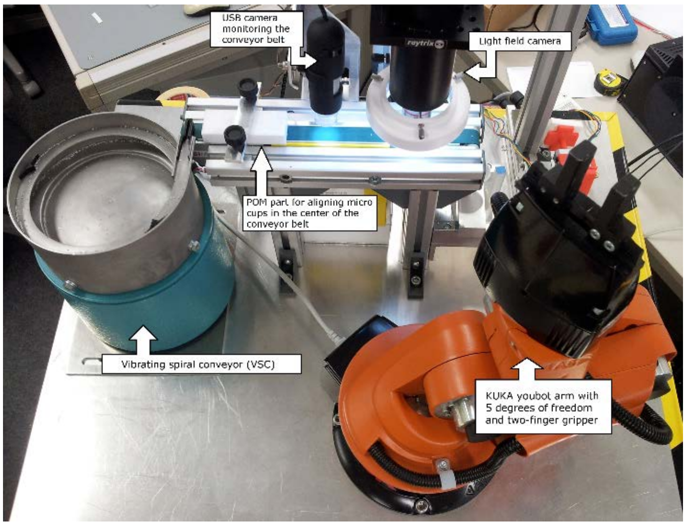

Figure 5 - The demonstration platform.

To ensure correct measurement of micro cups they have to be positioned correctly within the 2x2[mm] measurement window of the light field camera. With a cup diameter of ≤ 1[mm] this means they have to be positioned within a 1x1[mm] window to be fully measured. This is accomplished in width direction by the guiding element. For correct positioning in length direction, the conveyor belt has to be stopped precisely. This requires knowledge about the current position of the micro cup. While it is theoretically possible to recognize the part directly from the data of the light field camera, this approach is imposes unnecessary restrictions on the speed of the conveyor belt due to the small measurement area and limited frame rate.

The solution presented here consists of a second camera monitoring the whole width of the conveyor belt. This not only enables exact positioning of micro cups inside the small measurement window, but also allows for the collection of detailed data about positions and distances of micro cups. This data can then be used for evaluation of the setup as well as detection of parts incorrectly positioned in width direction.

Precise stoppage of the conveyor belt is realized by the use of a stepper motor. Following the detection of the part via the USB camera the motor receives a stop signal after a certain number of steps. The identification of the correct number of steps is part of the initial calibration process for the setup.

4 IMAGE PROCESSING CONCEPT FOR QUALITY INSPECTION

Image processing for defect classification is implemented using OpenCV as it provides a very good trade-off between computational efficiency, flexibility as well as transparency due to its open source code.

For effective defect classification of high-dimensional image data (512x512), the image is transformed to lower dimensional feature vectors. Two kinds of features are extracted: 2D geometry features, and depth features. We then used the obtained features to detect aforementioned defect classes:

1. Bottom tears.
2. Unequal wall height.
3. Wrinkles.

A cup is hence labeled as defect if at least one of these defects was detected.

Feature extraction is illustrated in figures 6 and 7. The measured parts contour information is extracted after applying an appropriate set of filters to the image (figure 6.B). Then the contour point distances to its center of mass are calculated (figure 6.C). The resulting vector D of these distances (figure 7.A) provides a description of the measured parts shape. For example the mean distance from center $\langle D \rangle$ can be used to identify bottom tears as they tend to show largely increased diameters.

For detection of wrinkles we separated local from global changes in D (i.e. due to a slightly oval cup form) by creating a filtered version D_f of D and subtracting it from D. The standard deviation of the resulting vector $D - D_f = D_{loc}$ is then used as an indicator for parts with wrinkles.

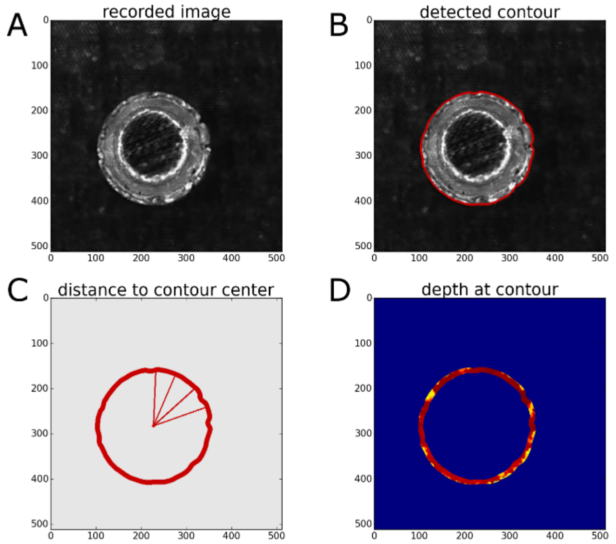

Figure 6 - Extraction of features. A: recorded image. B: detected contour. C: distances from contour centers. D: depth values around contour.

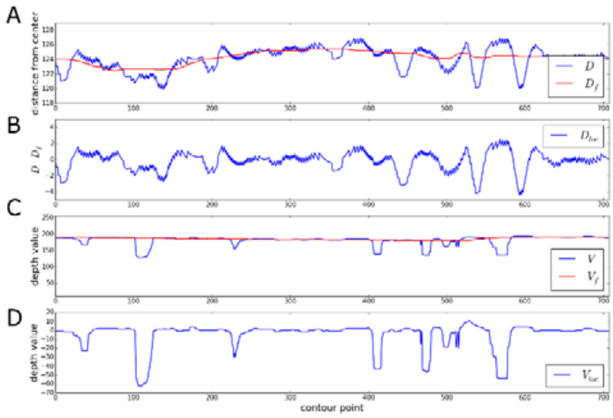

Figure 7 - Extracted features. A: Distances from contour center raw (D) and filtered (D_f). B: Local changes in distances D_{loc}, C: Median depth around contour: raw (V) and filtered (V_f). D: local changes in depth V_{loc}

Depth information can also help with detecting wrinkles that might not be easily identifiable from a standard 2D image. Depth features are extracted by taking the median depth value inside a small window around each point of the outer contour, creating depth vector V. Similar to the geometry features we separated local from global changes in the depth image by creating a median filtered depth vector V_f and subtracting it from the raw depth vector V, yielding $V - V_f = V_{loc}$. To identify wrinkles we then used the sum of the standard deviation of V_{loc} and D_{loc}: $F_{wrinkle}$ = std(V_{loc}) + std(D_{loc}).

Cups with unequal wall height show variations in V on a larger scale. To identify these global changes we use vector V_f as local variations are attenuated there. The standard deviation of V_f is then used as a feature for detecting cups with unequal wall height.

5 RESULTS/EVALUATION

5.1 Automatic defect detection

To evaluate the suitability of the extracted features for automatic defect detection we manually labeled a set of 312 images for the occurrence of different defects.

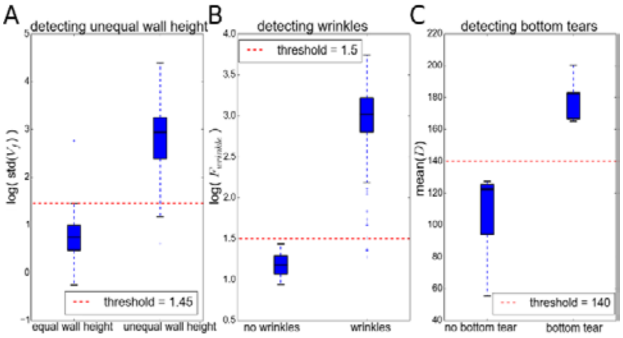

Figure 8 - Features for defect classification. A: The filtered depth vector V_f can be used for the identification of cups with unequal wall height. B: Adding the standard deviation of local variations in geometry (D_{loc}) and depth (V_{loc}) can be used to identify cups with wrinkles. C: Bottom tears can easily be identified by their high distance from center.

We then tested how well different features discriminate different defect classes. Results are shown in figure 8. For detection of cups with unequal wall height we used the standard deviation of the filtered depth vector V_f (figure 8.A). Wrinkles were identified via high values of $F_{wrinkle}$ and bottom tears are easily identified by their large diameter, i.e. high mean distance values $<D>$. Defect classification can hence be accomplished by applying appropriate thresholds to each of these features. In figure 8 example thresholds are marked which result in 99.3% of defective parts and 100% of sound parts being identified correctly.

5.2 Evaluation of demonstrator platform

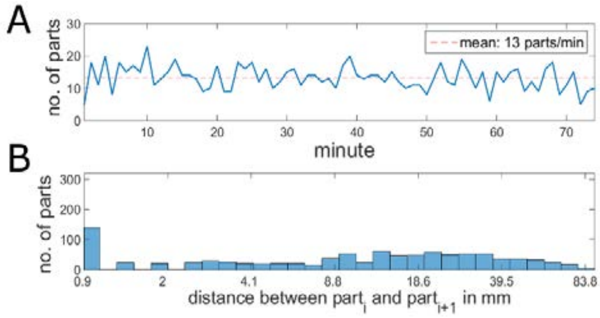

Figure 9 - Results of demonstrator platform evaluation. A: measured parts per minute. B: distribution of distances between cups on conveyor belt (note: x-axis is in log-scale).

Currently the demonstrator platform is able to measure ~13 parts per minute on average as shown in figure 9.A. To ensure good measurement speed as well as correct measurement and sorting, the distances between different parts must not be too small or too large. In figure 9.C we can see that most distances lie in the desired range of a few centimeters.

6 CONCLUSION

In this work we present a setup for the automatic detection of typical errors occurring during micro cup production. Via the use of a light field camera it is possible to identify all typical defect classes, i.e. unequal wall height, wrinkles and bottom tears, from a single recording. By integrating the camera into a demonstrating platform we are currently able to measure and classify ~13 parts per minute.

In order to realize an integration of the presented setup into micro production we are currently working on increasing measurement speed to match the high throughput rates of over 200 cups per minute accomplished by the micro cup production process developed at BIAS [4].

To achieve this three approaches will be taken. In the first place the speed of the demonstrating platform will be further optimized, via increasing the velocity of the conveyor belt as well as decreasing average and variance of distances between individual cups. Secondly the maximum measurement speed is limited by the computing speed for calculating the depth image and defect classification (currently ~0.5s). This upper limit will be increased both by using stronger hardware as well as optimizing the applied algorithms. In the long run the light field camera will be replaced by digital holography, which not only allows for higher measurement speed, but also a largely increased resolution [12]. Thirdly, after achieving a high enough measurement speed, throughput can easily be multiplied by utilizing multiple measurement units.

7 ACKNOWLEDGMENTS

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9 BIOGRAPHY

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Metrology – dimensional measurements, supporting the manufacturing industry

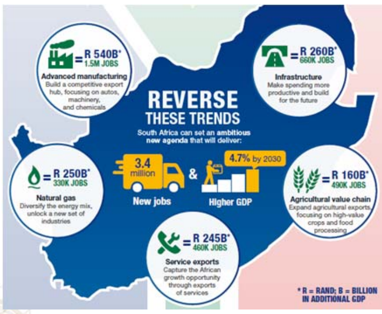
O Kruger

January 2016

Overview

- Manufacturing as one of the top priorities in SA
- Top priorities in manufacturing globally
- Automotive as one of the top priority in SA
- Tolerances required
- Changes in traceability chain for measurements
- New technologies – cell phone apps & additive manufacturing
- NMISA projects, machine tool evaluation & measuring equipment
- Conclusion

South Africa Big 5



Ref: Mckinsey- South Africa's Big Five Bold Priorities for inclusive growth

Table 3: Global market potential for key enabling technologies

	Current market size (~2006/08) bn USD	Expected size in 2015 (~2012/15) bn USD	Expected compound annual growth rate (%)
Nanotechnology	12	27	16
Micro and nanoelectronics	250	300	13
Industrial biotechnology	90	125	6
Photonics	230	480	8
Advanced materials	100	150	6

Technology	Industries to be affected	
3D Printing and personal fabrication	Electronics	Aerospace
	Energy (solar cells)	Food
	Pharmaceuticals	Clothing
Nanomaterials, Nano-tubes and graphene	Electronics	Instruments
	Energy (incl. green technologies)	Transport (automotive)
	Aerospace	Pharmaceuticals (medical imaging)
	Chemicals (sensors)	Textiles
Intelligent Polymers	Electronics	Energy
	Health	Textiles (smart interactive)

Ref: Manufacturing Europe's future, ISBN 978-90-78910-32-9

South Africa manufacturing strategy

	1994-1996	1996-1998	1998-2000	2000-2001
Low technology	1.59%	-0.98%	-3.45%	1.3%
Medium technology	8.85%	-0.84%	0.20%	-3.2%
High technology	14.25%	3.08%	11.84%	8.3%

Table 1. Growth rates versus technology intensity

Industry Sectors / Technology Focus Areas	Advanced Materials	Product Technologies	Production Technologies	Logistics	Cleaner Production Technologies	ICT in Manufacturing	Small & Medium Enterprise Development ¹	SQAM Technology issues¹
Automotive (& Transport)								
Metals (& Minerals)								
Chemicals								
Clothing & Textiles								
Craft								
Aerospace ¹								
Capital Goods ¹								

Figure 2. The sector/technology focus area matrix

5.5.2. Standards, Quality Assurance, Accreditation and Metrology (SQAM)

It is an internationally recognised fact that competitiveness is facilitated by a sound and efficient standards and conformity assessment infrastructure. A nation's ability to develop technical norms and to confidently and competently evaluate products against such norms is therefore of the utmost importance

White Paper on Science and Technology

DST-Advance manufacturing technology strategy

Role and mandate of NMISA

The NMISA is mandated to keep, maintain and disseminate the National Measurement Standards and demonstrate measurement equivalence for SA and the region (Act No. 18 of 2006)

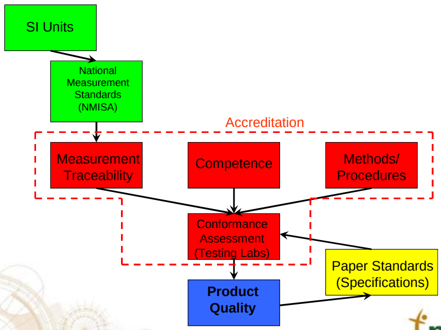
In addition the NMISA is responsible for the **application and maintenance of the Units (SI)** in SA

The NMISA also performs **reference analysis** and in a dispute, in any SA court, its results will be accepted as the **most correct value**

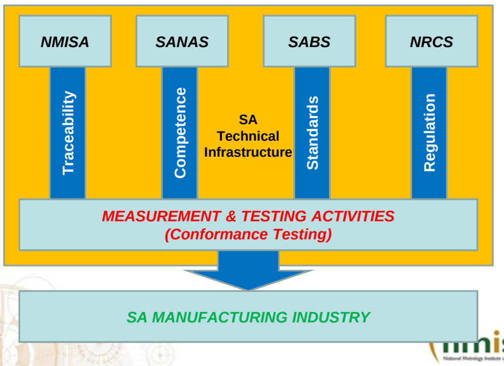
The History of NMISA in short

1947: The NPL was the 2nd laboratory of the CSIR
1956: NPRL obtained Copy 56 of the prototype of the Kg
1964: South Africa became the 40th signatory to the Metre Convention
1973: The Measurement Act appointed **the dti** as the responsible Dept for Metrology in SA
1999: The CSIR NML signed the CIPM MRA obo SA
2007: The NMISA was launched as part of the *Technical Infrastructure* (Quality Infrastructure) of SA

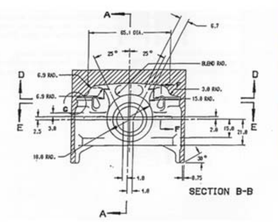
Harmonisation of conformance testing

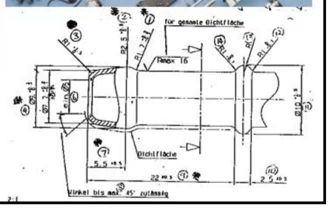


SA Technical Infrastructure



Tolerances





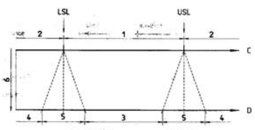
ISO 14253-1

Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment —

Part 1:
Decision rules for proving conformance or non-conformance with specifications

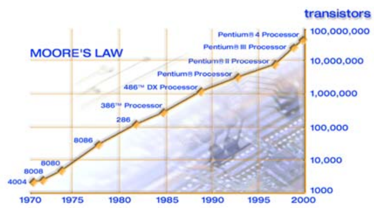
Spécification géométrique des produits (GPS) — Vérification par la mesure des pièces et des équipements de mesure —

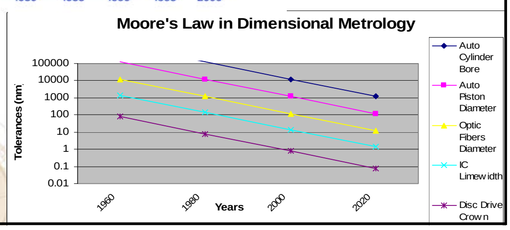
Partie 1: Règles de décision pour prouver la conformité ou la non-conformité à la spécification

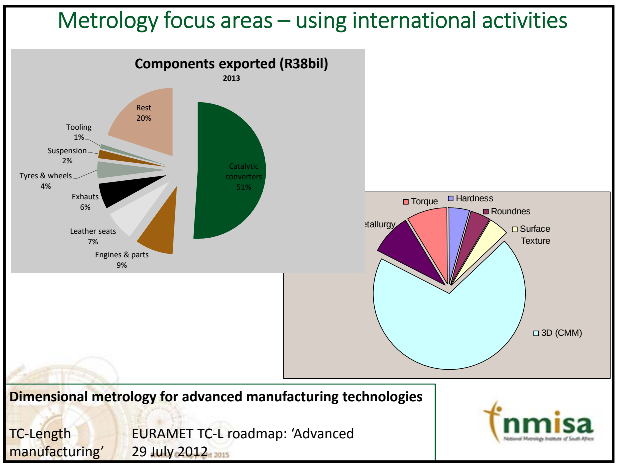


Key
C Design/specification phase
D Verification phase
1 Specification zone (in specification)
2 Out of specification
3 Conformance zone
4 Non-conformance zone
5 Uncertainty range
6 Increasing measurement uncertainty, U

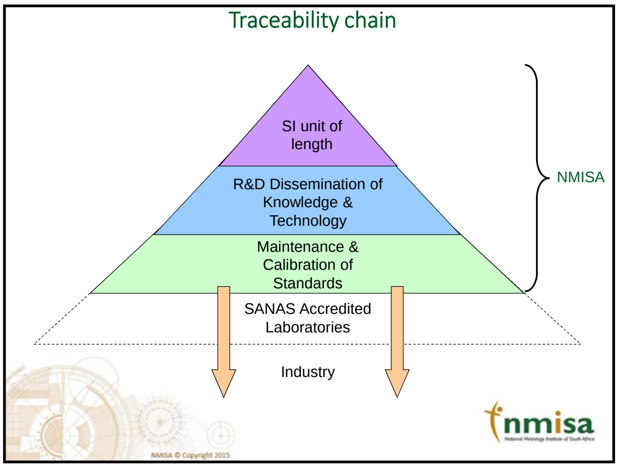
Advancements in manufacturing tolerances



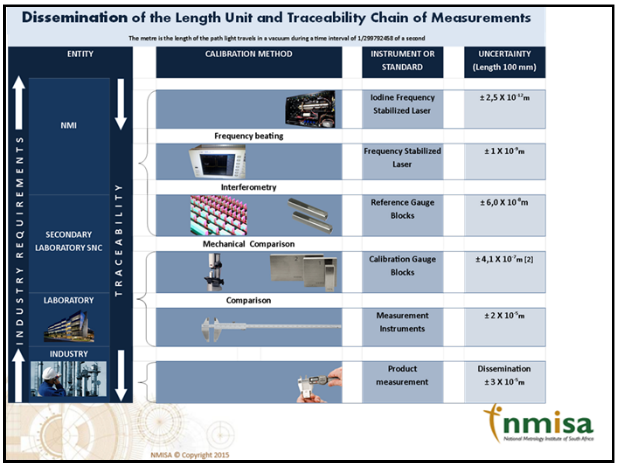




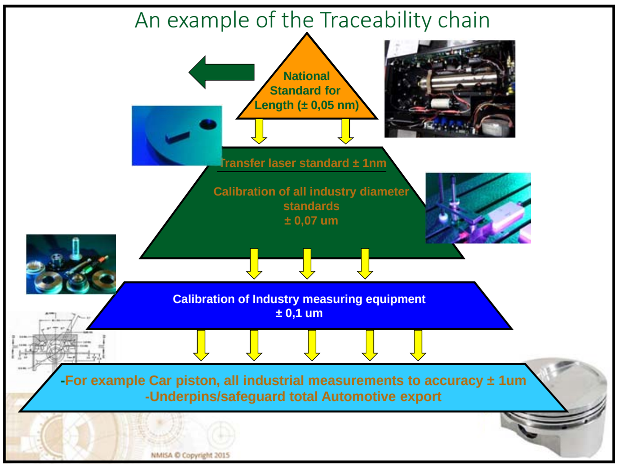
Metrology focus areas – using international activities
Components exported (R38bil)
2013
Rest 20%
Tooling 1%
Suspension 2%
Tyres & wheels 4%
Exhauts 6%
Leather seats 7%
Engines & parts 9%
Catalytic converters 51%
Torque
Hardness
Roundnes
Surface Texture
3D (CMM)
Dimensional metrology for advanced manufacturing technologies
TC-Length EURAMET TC-L roadmap: 'Advanced manufacturing' 29 July 2012



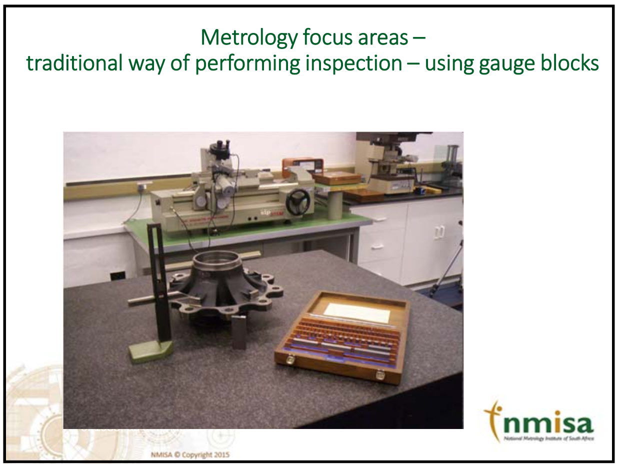
Traceability chain
SI unit of length
R&D Dissemination of Knowledge & Technology
Maintenance & Calibration of Standards
NMISA
SANAS Accredited Laboratories
Industry
NMISA © Copyright 2015



Dissemination of the Length Unit and Traceability Chain of Measurements
The metre is the length of the path light travels in a vacuum during a time interval of 1/299792458 of a second
ENTITY
CALIBRATION METHOD
INSTRUMENT OR STANDARD
UNCERTAINTY (Length 100 mm)
NMI
SECONDARY LABORATORY SNC
LABORATORY
INDUSTRY
INDUSTRY REQUIREMENTS
TRACEABILITY
Iodine Frequency Stabilized Laser
± 2,5 X 10-12m
Frequency beating
Frequency Stabilized Laser
± 1 X 10-9m
Interferometry
Reference Gauge Blocks
± 6,0 X 10-8m
Mechanical Comparison
Calibration Gauge Blocks
± 4,1 X 10-7m [2]
Comparison
Measurement Instruments
± 2 X 10-5m
Product measurement
Dissemination ± 3 X 10-5m
NMISA © Copyright 2015



An example of the Traceability chain
National Standard for Length (± 0,05 nm)
Transfer laser standard ± 1nm
Calibration of all industry diameter standards ± 0,07 um
Calibration of Industry measuring equipment ± 0,1 um
-For example Car piston, all industrial measurements to accuracy ± 1um
-Underpins/safeguard total Automotive export
NMISA © Copyright 2015



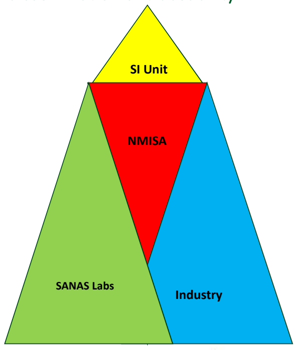
Metrology focus areas –
traditional way of performing inspection – using gauge blocks
NMISA © Copyright 2015

Metrology focus areas –
CMMs
X-ray source
sample
detector
rotation step by step
computed tomography / volume reconstruction
Figure 1: Illustration of the CT scanning method

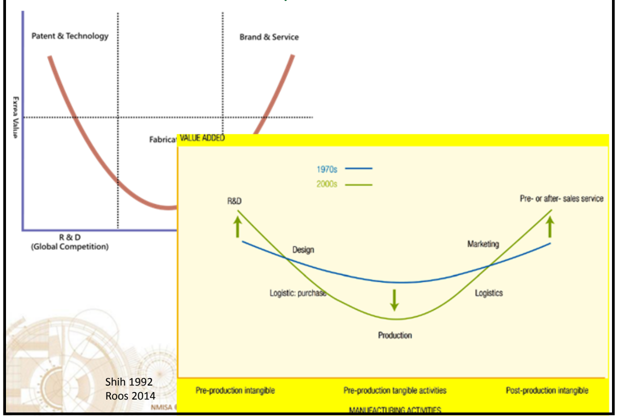
Metrology focus areas – Improvement in measuring equipment

To address the improvement and changes in measuring equipment Changes from traditional dissemination of traceability

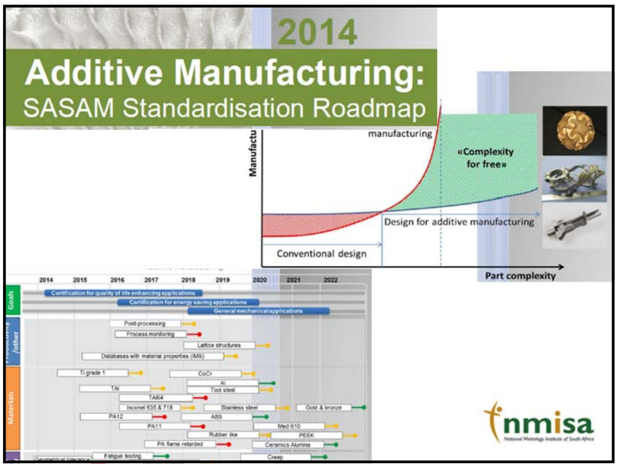
- SI Unit, definition of the metre, disseminated mainly through Iodine stabilised He-Ne laser, new definition makes it possible for any facility to have traceability through normal stabilised lasers
- Industry are having standards at SI unit level
- NMIs perform calibrations and measurements down to industry level.



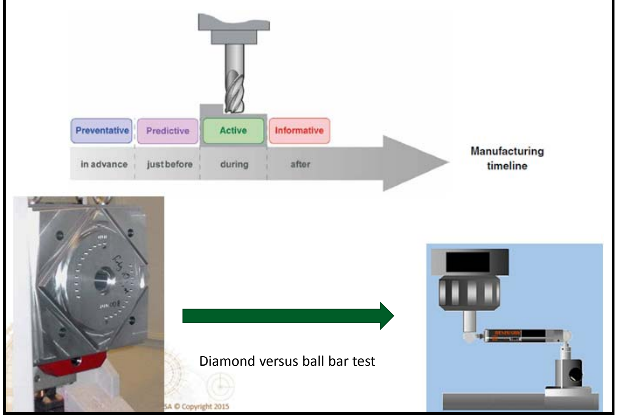
"Smiley face"



Shih 1992
Roos 2014



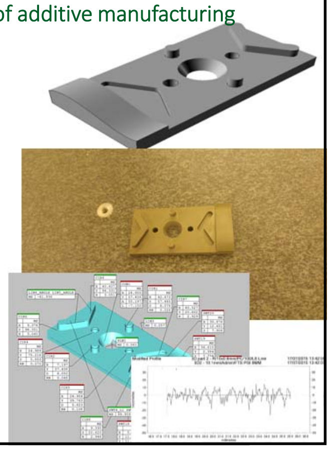
NMISA projects - Machine tool evaluation



Diamond versus ball bar test

NMISA projects - Evaluation of additive manufacturing

- CAD design
- Part printed in Titanium
- Measurements against CAD
  - Very bad surface texture straight of out of the machine



Three Dimensional printing, additive manufacturing.

- Modification of 3D printers by adding laser interferometers or other linear encoders

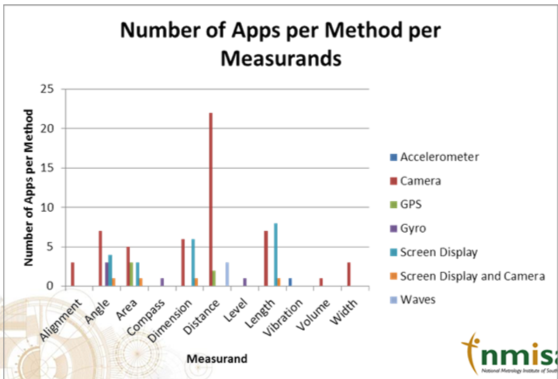
15

NMISA projects –

Cell phone apps. If you can image it, *there is probably an App for it already…*

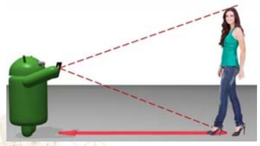
Total Number of Apps	62
Number of Unique Parameters Found	11
Number of Measurement Parameters by Apps	80
Number of Sensor Types	7

Dimensional Measurement Apps



Experimental Results so far

	Actual	Cell A	Cell B	Cell C	Cell D
Length	1600 ± 0,5	1562,34	1535,86	1600	1737,75
Width	1000 ± 0,5	1006,67	1003,54	1190	952,59
Depth	180 ± 0,5	207,91	225,71	180	257,67



Measuring equipment for industry

As part of the new strategy in NMISA, the length section is developing measuring systems for the local and Africa metrology community.

The line scale system was developed based on software which was required in-house for NMISA own line scale measuring systems. Twelve of these systems were delivered to African NMIs

Developing of specialised measuring equipment or standards designed for South Arica and the Africa continent.

- Calibration system for Tribor micrometers
- Micrometer setting piece
- Wool fibre metre

Conclusion

- The strategy is to service the South African and African industries through various R&D projects.
- The projects are selected to have an output which:
  - i) improve the National Measurement Standards
  - ii) improve measurements at industry level, traceability
  - Iii) develop measuring equipment for South Africa industry

nmisa
National Metrology Institute of South Africa

Characterization of Chip Morphology in Oblique Nose Turning employing High Speed Videography and Computed Tomography Technique

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Abstract

Simulation of industrial cutting processes employing physics based numerical models provide valuable insights into its deformation mechanics. Evaluating such models through chip studies require characterizing complex geometric features like chip shape, and chip curl. In this study, a characterization methodology is developed employing tools like computed tomography (CT) and high speed imaging. The methodology is used to characterize chip curl parameters such as chip side flow angle, chip up curl and chip side curl in oblique nose turning process. To evaluate the methodology, AISI 1045 steel is machined over a range of machining parameters and the chips obtained are characterized. The study shows that the employed methodology can be used to characterize varying chip curl geometries in nose turning process. CT technique is additionally employed when the chips are significantly deformed. The study also shows that the developed characterization methodology could be used to evaluate physics based numerical models.

Keywords

Chip curl, high speed videography, computed tomography

1 INTRODUCTION

Machining is an important manufacturing process for realization of precision engineered metallic products. Due to its position being close to the end of a production sequence both in automotive and aerospace industries [1], machining process has to have high reliability. To achieve this, every aspect of machining process starting from chip formation mechanics to residual stresses in work piece surfaces and their inter relationship is studied.

Modelling of chip formation process in machining employing numerical methods has been carried out for more than three decades starting from the orthogonal machining process in the 1970s [2] to more challenging industrially relevant cutting processes such as turning, drilling and milling in the 2000s [3][4][5].Literature research shows that these models have been evaluated primarily by its cutting force prediction capability. This is primarily due to the need of cutting forces experienced by a cutting tool as an input for modelling of dynamic behaviour of machine tools [6]. Other aspects such as chip morphology and residual stresses have gained significance only in the past 2 decades [7].

From a cutting tool design point of view, the flow of chip on the rake face is important as this directly influences the heat transfer between the cutting tool and chip. This indirectly influences the progression of wear in the rake face, thereby determining the cutting tool life. The chip flow also influences the direction of cutting forces and through chip curl influences chip breaking significantly. By controlling chip flow direction and chip curl chip breakage could be improved.

To utilize chip shape and chip curl as parameters for evaluating a cutting model's efficiency, chip shape and chip curl characterization methodologies need to be developed for industrially relevant cutting processes. In this regard, characterization tools were developed for orthogonal machining process in a previous work where computed tomography was employed for the evaluation of chip morphology for orthogonal cutting process [8].

In the present paper, for the accurate characterization of chip morphology in an industrially relevant nose turning process, in addition to computed tomography, high speed filming of the cutting process was employed to model the chip morphology. The flow of chip on the rake face and curling of the chip during the cutting process is described by a model developed by Kharkevich et al [9]–[11]. The most important aspect of this work is the development of a characterization methodology for chip morphology in the nose turning process.

1.1 Geometric modelling of chip morphology

The term 'chip morphology' is used to define the complete chip geometry which includes both chip shape and chip curl. Chip shape is the cross section of the chip in the direction of chip flow. Chip curl, on the other hand is the variation of chip geometry in the chip flow direction on the rake face and is characterized by chip up curl, chip side curl and chip side flow angle[12].

With the aim of this work being to develop a methodology to characterize chip morphology and in particular chip curl in oblique turning process, it is imperative that the complete description of parameters describing the chip shape and chip curl is to be established although chip shape is not the focus of this study.

1.1.1 Chip shape

The chip shape is mainly categorized into continuous, segmented and discontinuous. The chip shape changes due to the work piece material's response to the cutting conditions under which machining takes place. With increase in cutting speed or increase in feed rate, the chip shape is altered from a continuous to segmented chip shape. The variation of chip shape from continuous to segmented with increase in cutting speed is primarily due to the reduction in time for the heat generated in the primary shear zone to move into the work piece, chip and tool leading to adiabatic heating conditions and is termed adiabatic shear. The variation of chip shape with increase in feed rate is attributed to the tensile stresses at the tool cutting edge - work piece contact and is termed ductile failure [13]. The chip shape is be characterized by the parameters, maximum chip thickness (h_{max}), minimum chip thickness (h_{min}), average chip thickness (Δh) and chip segmentation length (ls) and is shown in Figure 1 (a). Chip segmentation length is also characterized by the segmentation intensity ratio [14].

1.1.2 Chip curl

Fundamental and extensive studies related of chip curl were carried out extensively by Nakayama [15], Spaans [16] and Jawahir [17] from 1950s to 1990s.Chip curl is defined geometrically by a combination of chip up curl (ρ_u), chip side curl (ρ_s) and chip flow angles. When the chip flows on rake face, the chip's curvature 'C' in Figure 1 (b) is the chip curl in 3D. The radius of curvature of the chip's curvature 'C' on the YZ plane is termed chip up curl

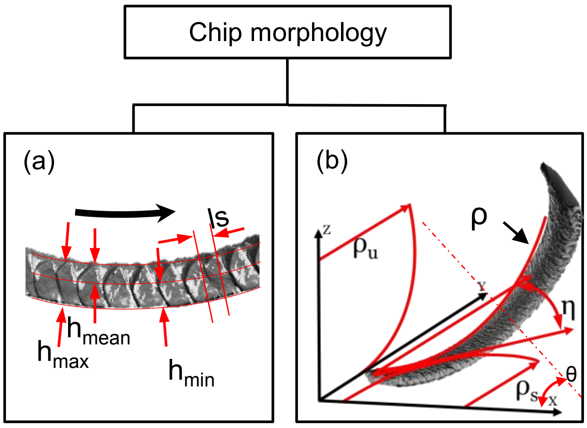

Figure 1 - Components of chip morphology of chip in nose turning process (a) Chip shape (b) Chip curl & Chip flow angle based on Kharkevich's model

and is measured by the chip up curl radius (ρ_u). Similarly, the radius of curvature on the XY plane is termed chip side curl and is measured by chip side curl radius (ρ_s) and XY plane lies on the rake face. Chip up curl and chip side curl are defined when chip flows on the rake face during the cutting process and is termed 'chip in process' curl parameters. Measurement of the chip curl parameters for varying cutting parameters and tool geometry parameters during the cutting process accurately is a practical difficulty. To overcome this challenge, Kharkevich et al [10], developed a model where the above mentioned 'chip in process' curl parameters are calculated from geometrical parameters measured from chips collected after the experimental investigation and can be termed 'chip in hand' curl parameters. The Kharkevich model is more suited when the chip does not hit the tool flank surface and flows freely on the rake face.

The chip up curl radius (ρ_u) (Eqn 1) and chip side curl radius (ρ_s) (Eqn 2) are calculated as follows according to the model.

$$\rho_u = \frac{\rho}{\cos\eta\cos\theta\sqrt{1 - sin^2\eta cos^2\theta}} \qquad (Eqn\ 1)$$

$$\rho_s = \frac{\rho}{\sin\theta\sqrt{1 - sin^2\eta cos^2\theta}} \qquad (Eqn\ 2)$$

Where ρ defines the chip curl, η defines the chip side curl angle deviation and θ defines the tilt angle.

1.1.3 Chip flow angle

Chip flow angle in addition to chip up curl and chip side curl is required for the complete geometric description of chip curl in oblique turning. Chip flow angle in a plane perpendicular to the cutting edge and rake face is termed the chip back flow angle (η_b) and the chip flow angle on the rake face plane is termed the chip side flow angle (η_s). Chip back flow angle is related directly to the restricted contact or the land geometry in the cutting edge. Rake angle, chip thickness and land length influences the chip back flow angle. Chip back flow angle is difficult to measure for nose turning with commercial inserts employing chip breaker geometries. Chip side flow angle on the other hand can be measured easily in nose turning process. The most widely used model for the prediction of chip side flow angle is the Colwell line [18] which joins the two end points of uncut chip area on the rake face.

2 METHODOLOGY AND EXPERIMENTAL INVESTIGATION:

The study is carried out with the hypothesis that the characterization methodology employing High speed videography, Computed tomography and Kharkevich model can be used to characterize chip curl in nose turning and can be used to evaluate numerical models which simulate chip formation. Machining tests were carried out employing commercial chip breaker geometry and the chip curl were characterized. The employed characterization methodology shows the capability to characterize chip morphology for varying cutting conditions.

2.1 Experimental investigation:

To test the hypothesis, nose turning were carried out on AISI 1045 steel with inserts employing commercially available chip breaker geometry (CNMG120408–MM) [19]. The specification of the work piece material tests are presented in this section which include chemical composition, hardness measurements and material microstructure analysis performed. The chemical composition of the work piece is as shown in Table 1.

Table 1 - Chemical composition of AISI 1045 steel

C	Mn	Si	P	S	Cu
0.44	0.73	0.211	0.007	0.021	0.04
Cr	**Ni**	**Mo**	**V**	**Sn**	**As**
0.03	0.06	0.012	0.002	0.003	0.002
Ti	**Al**	**N**	**H_2**		**Fe**
0.002	0.034	0.0062	1.17 ppm		>98.3

The work piece hardness was measured to be 170 ± 20 HV. To circumvent the variation in the hardness, the cutting experiments were carried out at the same radial distance from center. The local hardness measurement where machining was carried out is measured to be 180±7 HV. In addition to hardness measurement, tensile tests were carried out and is tabulated in Table 2.

Table 2 - Mechanical properties of AISI 1045 steel

Yield strength, (Re)	395 MPa
Ultimate tensile strength (Rm)	675 MPa
Percentage elongation after fracture (A5)	26.4 %
Percentage reduction in area (Z)	42.2 %

The experimental investigations were carried out in a Köping lathe as this provided better positioning of high speed imaging systems. Halogen lamps were positioned to improve the quality of imaging as the machining process was studied with a resolution of 1280 X 720 and 7000 frames per sec. The cutting conditions employed are provided in Table 3. The cutting conditions were employed to produce varied chip morphologies that include both chip up curl dominated chips and chip side curl dominated chips.

Table 3 - Cutting parameters employed

Cutting speed (m/min)	180
Feed rate (mm/rev)	0.05, 0.15, 0.3, 0.5
Depth of cut (mm)	0.5,1,2
Insert geometry	CNMG120408 – MM
Insert material	H13A (no coating)
Edge radius (µm)	30
Tool holder geometry	PCLNR 2525M12

2.2 Chip characterization methodology

The chip characterization methodology is to be able to capture the variation of chip shape from continuous to segmented, chip curl and chip flow angle for varying cutting conditions and cutting tool geometries.

2.2.1 Chip shape characterization

The CT methodology employed for characterizing chip shape is detailed in a previous work [8]. The methodology developed for orthogonal turning process can be used without any modification or difficulty for any industrial machining process. Figure 2 shows that chip geometry obtained from CT measurement can be used to study both chip shape variation and chip curl variation. The CT methodology enables in the study of variation of chip segmentation across the chip width and will enable to study in detail the influence of different features in a chip breaker geometry. The variation of chip segmentation across the chip width can also be accessed quantitatively, although it is not the aim of this work.

Table 4 - Chip morphology characteristic and employed associated characterization tool

Chip morphology	Characterization tool
Chip shape	Computed tomography (CT)
Chip curl	Kharkevich model + CT
Chip flow angle	High speed imaging

2.2.2 Chip curl characterization

The chip curl is characterized as mentioned earlier employing the 'chip in hand' to 'chip in process' transformation by Kharkevich et al [10] and is depicted in Figure 3. The 'chip in hand' chip curl parameters are chip outer diameter (ρ_0), chip inner diameter (ρ_i) and the chip cross section parameters |p| and |h1|. Characterization employing these parameters lead to a larger error when the chips deviate from the screw type chip due to interaction with the tool or work piece. To overcome this shortcoming, CT technique could be used to characterize chip up curl and chip side curl directly as shown in Figure 2.

2.2.3 Chip side flow angle characterization:

The chip side flow angle is used in this work to characterize the chip flow on the rake face. The chip side flow angle is measured from the high speed images for all cutting conditions. This provides the

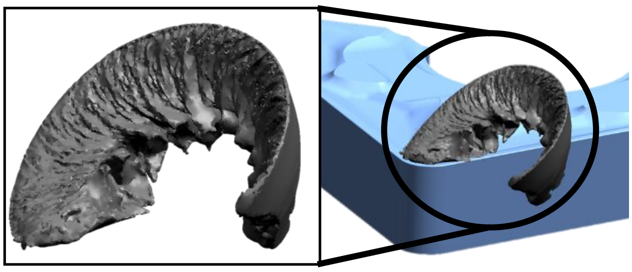

Figure 2 - Chip CAD model (obtained from CT) positioned in the cutting tool rake face.

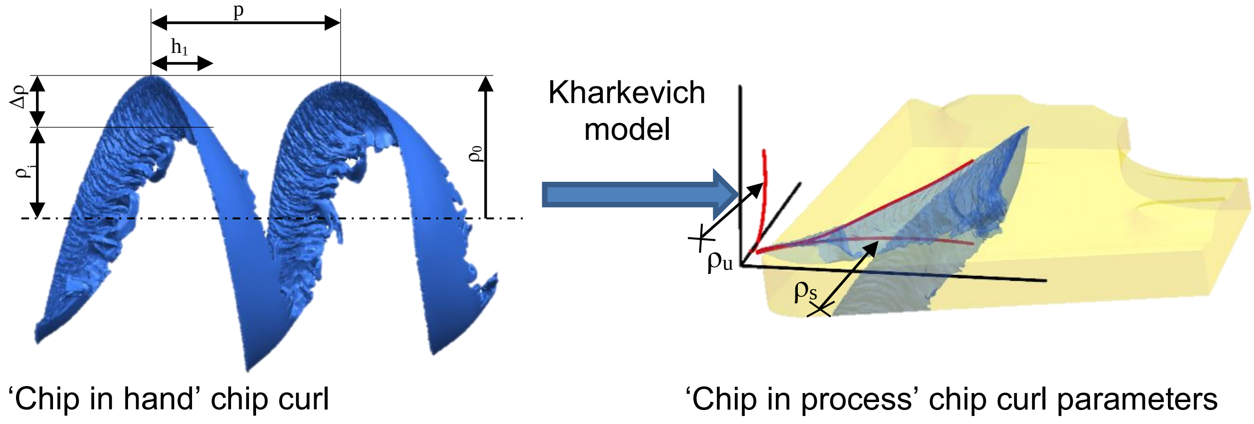

Figure 3 - Transformation of 'Chip in hand' chip curl parameters to 'Chip in process' chip curl parameters employing Kharkevich model

possibility to observe chip side curl variation due to contact with the chip former back wall or work piece.

3 RESULTS

With the aim of evaluating the measurement methodology developed in this work to characterize chip morphology, the experimental investigations were carried out. The chips were collected, measured and the chip curl parameters were calculated. In order to evaluate the accuracy of this methodology, tilt angle ,θ, calculated using Kharkevich model were compared with the tilt angle measured using images obtained from experimental investigation for certain cutting conditions and are found to be accurate within ±2° (Table 5).

Table 5 - Comparison of tilt angle for different feed rate (F) and depth of cut (D)

Cutting	θ (calculated)	θ (measured)
F:0.05 – D:2	8.3	8.5
F:0.30 – D:2	26.2	27
F:0.50 – D:1	51.7	54

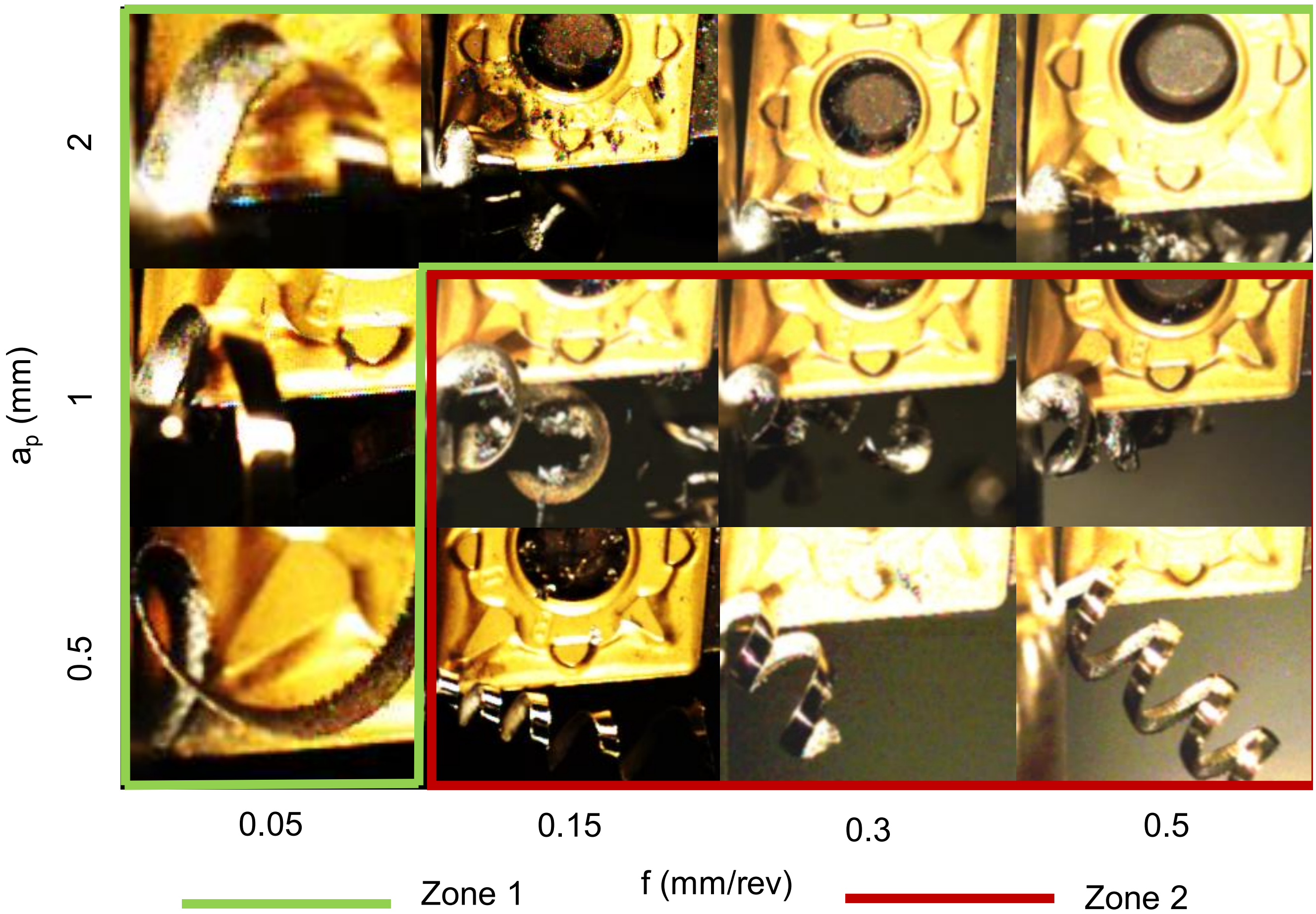

Figure 4 - Chip flow on the rake face observed using high speed videography and chip morphologies analysed using the employed methodology

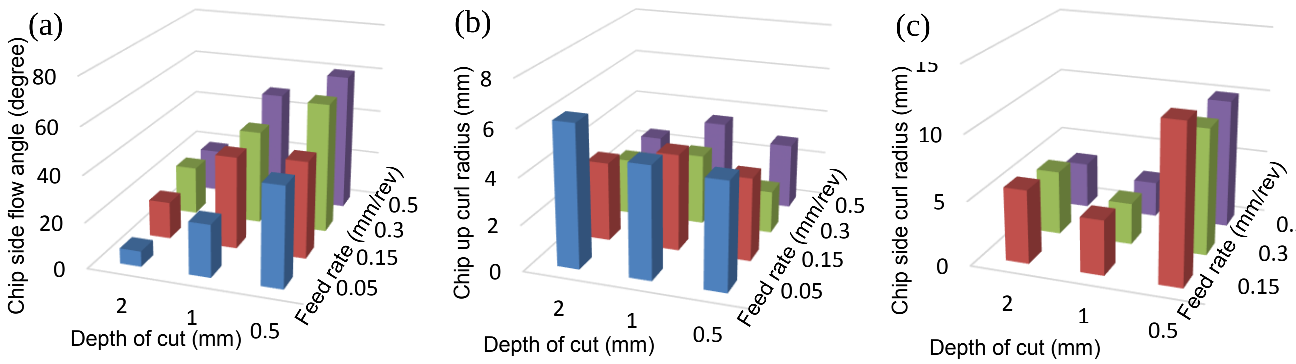

Figure 5 - Variation of (a) chip side flow angle (degree) (b) chip up curl radius (mm) and (c) chip side curl radius (mm) for varying feed rate and depth of cut in nose turning of AISI 1045 steel.

This clearly shows the ability of the method employed to measure the chip curl parameters over the cutting parameters in which it is tested and where the chip morphologies of chip up curl and chip side curl are the predominant chip curl phenomena.

3.1 Chip flow angle

Figure 4 shows the variation of chip curl and the different chip morphologies observed. The high speed images were used to measure the chip side flow angle when the chip is not obstructed by the flank face or the work piece surface. The chip chart is divided into two zones, zone 1 and zone 2. Zone 1 covers the lowest feed rate of 0.05 mm and for all depth of cuts and highest depth of cut of 2 mm for all feed ranges. Zone 2 encompasses the remaining parameters in the experimental area. Figure 5 (a) shows that the chips with a larger chip flow angle are obtained in zone 2 and in zone 1, the chips have predominantly a smaller chip flow angle.

3.2 Chip up curl & Chip side curl

The variation of chip curl over the entire feed rate and depth of cut range is calculated from chips obtained in experimental investigation. Figure 5 (b) shows that the chip up curl reduces as the feed rate increases for a constant depth of cut. On the other hand, the chip up curl is less influenced with increase in depth of cut at a constant feed rate. The maximum decrease of chip up curl is observed at a constant feed rate of f=0.05 mm/rev. In Figure 5 (c), the chip side curl is plotted for feed rate of 0.15 mm/rev to 0.5 mm / rev for the chip up curl radius at a feed rate of 0.05 mm /r rev is 3 to 4 times the maximum value at higher feed rates.

4 DISCUSSION

The employed chip curl characterization methodology is validated by comparing the tilt angle parameter calculated by the Kharkevich model and tilt angle parameter measured from high speed images. The measured and calculated values are within the range of statistical spread and measurement error.

Using the above methodology it is now possible to compare the chip morphology predicted by finite element simulations and experimental investigations for practical machining conditions. The chip side flow angle is largely up curl dominated in zone 1 for both conditions of low feed rate and large depth of cut. The domination of up curl at low feed rates can be attributed to the active cutting edge being a plane rake face tool. It has been shown previously that with the active chip contact length being less than the land length, the chip forming process with a groove tool is equal to cutting with the plane rake face tool [20]. At higher depth of cut of 2 mm and for all feed rates employed, the influence of the main cutting edge is larger than the nose cutting leading to a predominantly up curled chip. On the other hand, in zone 2, the chip flow angle is influenced by the chip former geometry and the chip is formed or its flow direction is altered after it leaves the tool chip contact area. The reduction of chip side curl radius with increase in depth of cut is also attributed to the increasing influence of the main cutting edge than the nose radius. At a lower depth of cut, the non-perpendicularity of the cutting edge with the cutting direction leads to a larger side curl radius.

5 CONCLUSION

In this work, a characterization methodology to characterize chip morphology during experimental investigation for nose turning process is developed. Chip curl parameters such as chip side flow angle, chip up curl and chip side curl are characterized by a combination of high speed videography, a mathematical model developed by Kharkevich et al and computed tomography technique. The variation of chip side flow angle, chip up curl and chip side curl for varying cutting conditions is examined. The results show that the developed methodology can be used to evaluate chip morphology prediction of physics based numerical models for nose turning process.

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7 BIOGRAPHY

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Efficient Manufacturing of Tribological Surfaces by Turning Technologies with Alternating Movements

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Abstract
The influence of surface properties on the tribological behaviour of sliding parts is understood better and better due to the investigations during the last decades. However, many finishing processes are time-consuming and too expensive for wide serial applications. Efficient machining methods for the shape cutting with an included finishing of the parts are therefore necessary in an industrial scope.The paper presents precision machining technologies using additional fast alternating movements to modify the kinematics of the turning process. These technologies enable the generation of tribologically active and highly precise surfaces with a modified microgeometry. Two different technologies involving a beneficial surface modification are described. The surfaces generated are examined in detail. Tribological investigations show a significant improvement of the sliding behaviour for the specimens with a modified surface structure compared to unstructured specimens.

Keywords
Surface modification, Tribology, Turning

1 INTRODUCTION

The development of mechanical components is characterised by rising demands concerning functionality, quality as well as resource and energy efficiency. These requirements include the friction and the wear mechanisms of sliding components. Hence, the improvement of tribological properties is a key factor for the realisation of energy efficient products and components.

Turning is a widely applied process for the manufacturing of rotationally symmetric parts, because it enables a comparably efficient machining with high accuracy. However, in many tribological applications, ressource intensive and time consuming surface finishing processes are still required for a suitable adjustment of the surface properties. For this reason, the present work aims on the use of the turning process for the manufacturing of tribologically optimised surfaces. With improved cutting technologies, rough and finish machining can be combined in one process, which leads to the opportunity of a reduction of process steps or a process substitution, respectively [1].

2 TWIST-REDUCED TURNING

2.1 Approach

In many applications, for example sealing and bearing components, turned surfaces are not suitable because of their twist structure. This structure is similar to a micro thread and may cause leakage in sealing systems or an irregular distribution of the lubricant in plain bearing systems.

Twist structures on surfaces can be characterised by different parameters. These parameters are described by the Mercedes Benz Standard MBN 31007-7 for macro twist structures. The main lead parameters are presented in Figure 1.

With the aim to reduce or eliminate the twist structure and the resulting conveying effect for lubricants, the number of threads *DG* or the supply cross section *DF* has to be reduced. As a possible solution for this, the application of start-stop turning was introduced in [2]. In this process, the tool moves discontinuously and stays at every specific position for the minimum time of one revolution of the workpiece (Figure 2).

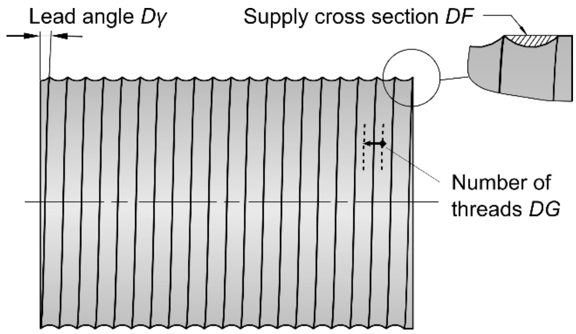


Figure 1 - Characteristic twist parameters for conventionally turned surfaces.

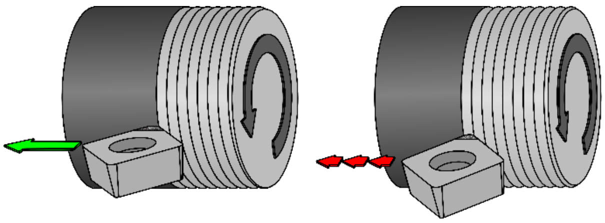


Figure 2 - Conventional turning (left) compared with start-stop turning (right).

For the start-stop turning process a highly dynamic movement with great accelerations of the cutting tool is necessary. The generation of this movement can be realised by a superimposition of two separate motions, namely a defined alternating movement on the one hand and a constant feed motion of the machine axis on the other hand. These two movements and the resulting kinematic are illustrated in Figure 3.

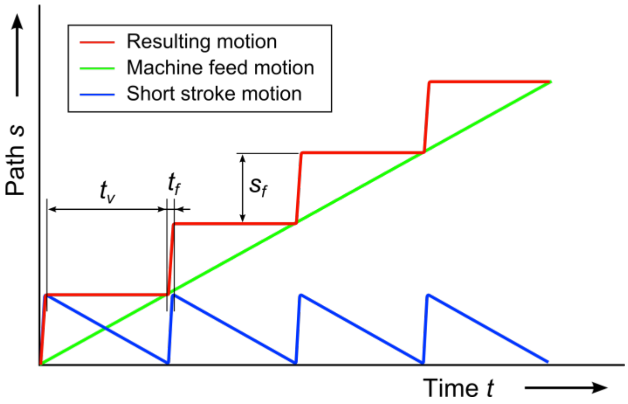


Figure 3 - Kinematics of the developed start-stop turning process.

In the following section a newly developed setup for the practical realisation of the start-stop motion is presented. Turning experiments are conducted using hardened steel specimens. With the aim to validate the resulting surface twist structure using the lead parameters described, measured data of the surfaces are analysed.

2.2 Experimental setup

Figure 4 shows the newly developed setup for the realisation of start-stop turning. The tool is mounted on a highly precise short stroke actuator with air bearings generating the translational movement. The short stroke actuator was integrated into a precision lathe SPINNER PD 32. An independent, programmable controller is used to adjust the alternating movement.

A CBN tipped and chamfered indexable insert with the specification CCGW 060202 and a wiper cutting edge was applied for the hard turning experiments. The tool geometry is shown in Figure 5.

The process was carried out dry and the cutting parameters were kept constant at $v_c = 180$ m/min and $a_p = 0.05$ mm. The specimens of hardened steel 42CrMo4 ((58 + 2) HRC) with a width of the surface generated of 12.5 mm were machined to a final diameter of 80 mm. Because of a limited dynamic stability of the short stroke actuator its maximum jerk was set at 50 m/s³ and the resulting feed velocity at 200 mm/min. To ensure a retention of the tool position for at least one revolution for this case a retention time of $t_v \approx 89$ ms was applied ($v_c = 180$ m/min, d = 80 mm → n = 716 min^{-1}), which corresponds to an angle of revolution of about 380°. The stroke length s_f was 70 µm. The feed velocity of the machine axis, which has to be in compliance with the absolute value of the retraction movement velocity of the short stroke actuator, amounted to 47 mm/min. Furthermore, for the purpose of comparative considerations, some specimens were turned with the conventional kinematics (Figure 2, left picture) using the same tool geometry, cutting speed and depth of cut as for the examinations with the short stroke actuator. However, the feed was fixed to 0.12 mm for the conventional turning kinematics.

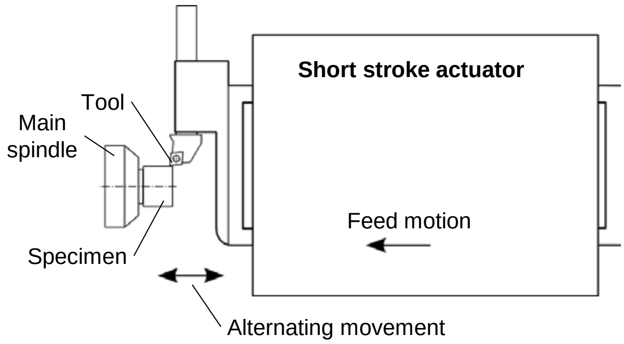


Figure 4 - Setup for the start-stop turning.

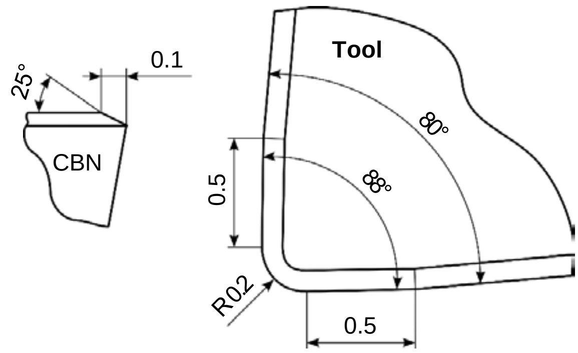


Figure 5 - Tool geometry for the turning experiments.

After the turning experiments, the surface structure was measured using several tactile instruments. The measuring unit Mahr LD120 was applied for roughness measurements. The twist structure was captured with the instrument Mahr MMQ200 recording 72 lines with a length of 2 mm and an angular distance of 5°. The twist analysis according to the standard MBN 31007-7 was performed with the software MountainsMap® processing the data from the Mahr MMQ200 instrument. The twist parameters were calculated for a measuring field with a length of 2 mm.

2.3 Experimental results

Figure 6 shows a detail of a surface generated with the conventional turning kinematics after suitable preparation with the software MountainsMap according to the standard MBN 31007-7. The surface exhibits a one-start twist structure with a lead angle *Dγ* of approximately -0.0274° resulting from the feed and the diameter of the specimen. The negative sign indicates a left hand twist structure. The period length *DP* corresponds exactly to the feed of 0.12 mm. However, there is a theoretical supply cross section per turn of about 50 µm², which can cause an undesired conveying of lubricant. Moreover, the surface roughness profile is formed regularly and has a roughness depth *Rz* of about 1.6 µm.

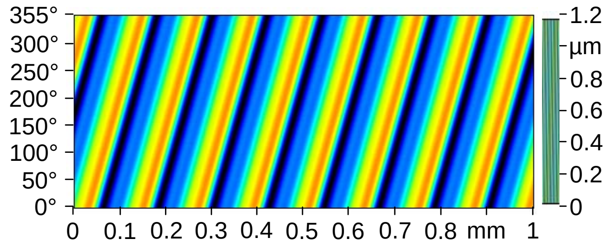


Figure 6 - Twist structure of a surface generated with the conventional turning kinematics.

A detail of a surface generated with start-stop turning after a preparation analogous to Figure 6 is presented in Figure 7. The twist structure is regularly formed. But, because of a lead angle equal to zero the number of threads and the theoretical supply cross section per turn

$$DFu = DG \cdot DF \tag{1}$$

are zero, too.

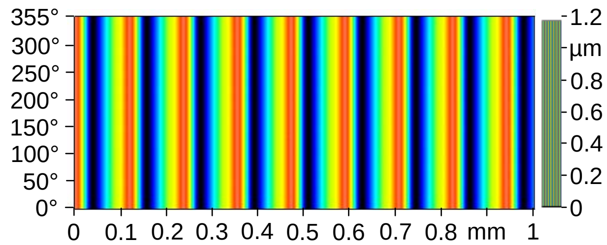


Figure 7 - Surface structure generated with start-stop turning kinematics.
(v_c = 180 m/min; $t_v \approx$ 89 ms; s_f = 70 µm)

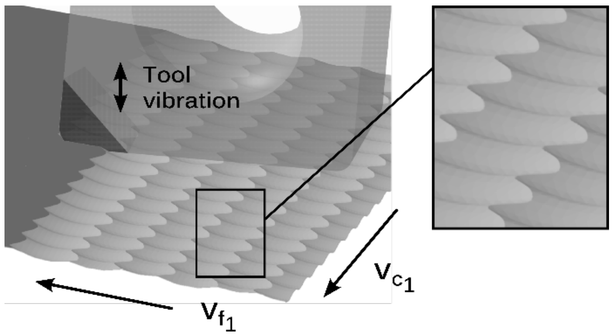
It can be expected, that there is no significant conveying effect on lubricants. The period length *DP* is much larger than the stroke length s_f and amounts to 0.117 mm. This results from the machine feed motion during the forward stroke. The large difference between the period length and the stroke length can be decreased markedly using an actuator with a higher dynamic stability. The surface roughness profile is less regular. Consequently, the surface roughness depth *Rz* is higher than for the surface generated with conventional turning kinematics and amounts to about 2.3 µm.

3 MICROSTRUCTURING BY VIBRATION-ASSISTED TURNING

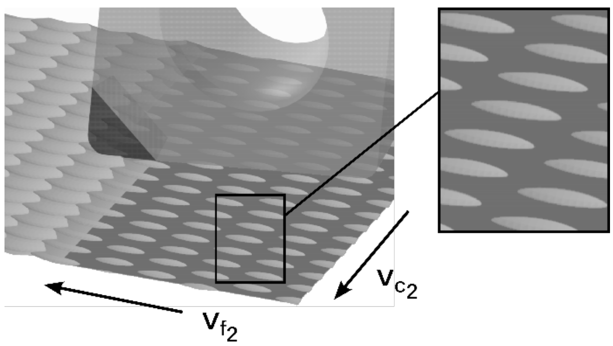
3.1 Approach

Surface microstructuring was identified as an effective method for friction and wear reduction of lubricated sliding systems. Several types of microstructures were already developed and evaluated by hydrodynamic simulation studies and experimental investigations. It could be confirmed that closed dimples offer better capability for friction reduction compared to open surface microstructures [3].

With the aim to produce microstructured surfaces with closed dimples by cutting with geometrically defined cutting edge, a vibration-assisted turning (VAT) process including two cutting steps was developed. These two process steps are visualised schematically in Figure 8. Only during the first step, tool vibration in the direction perpendicular to the machined surface is used to generate periodic surface structures (Figure 8a). The second machining step is the finishing operation, where closed microstructures are realised by using a very small depth of cut (Figure 8b).



(a) First machining step - roughing



(b) Second machining step - finishing

Figure 8 - Generation of surface microstructures by vibration-assisted turning.

3.2 Process parameters

Because of the two machining steps on the one hand and the vibration assistance on the other hand, several parameters have to be defined for the design of the process. Table 1 gives an overview of the most relevant parameters for the two-stage process.

Turning process	*Vibration assistance*	*Tool*
Feeds f_1, f_2	Amplitude $A_{p\text{-}p}$	Geometry
Cutting speeds v_{c_1}, v_{c_2}	Frequency f_v	Material

Table 1 - VAT process parameters.

The process parameters have a fundamental influence on the resulting surface structure including the geometry and the arrangement of the microstructures. These relationships were already analysed in [4] using a kinematic model implemented in Matlab. However, there was not yet discussed the influence of the machining parameters on the process efficiency, respectively.

A substantial advantage of generating microstructures using a process with geometrically defined cutting edge is the achievable process efficiency. In this context, the machined area per time A_m/t_m and the number of microstructures per machining time n_{str}/t_m are practically of importance. Assuming that the process parameters are kept constant, these characteristic values can be calculated considering the two separate machining steps as follows:

$$\frac{A_m}{t_m} = \frac{f_1 \cdot f_2 \cdot v_{c_1} \cdot v_{c_2}}{f_1 \cdot v_{c_1} + f_2 \cdot v_{c_2}}, \tag{2}$$

$$\frac{n_{str}}{t_m} = \frac{f_v \cdot f_2 \cdot v_{c_2}}{f_1 \cdot v_{c_1} + f_2 \cdot v_{c_2}}. \tag{3}$$

In order to emphasise the potential of the method, these parameters are calculated exemplarily for the used parameter combinations in section 3.4.1.

3.3 Experimental setup

For the experiments, ultrasonic vibrations with a frequency of $f_v \approx 24$ kHz and an amplitude (peak to peak) of $A_{p\text{-}p} \approx 10.4$ µm were generated. The vibration system manufactured by Hielscher / Devad (Germany) was therefore integrated into the lathe mentioned in section 2.2, as Figure 9 shows.

For the machining of the bronze specimens (CuSn8P, EN CW 459 K), a monocrystalline diamond tipped indexable insert with a sharp cutting edge featuring an cutting edge radius less than 1 µm was applied. Furthermore, the clearance angle of the tool was 7°, the corner radius 0.4 mm and the tool included angle amounted to 80°.

For the turning experiments and the following tribological measurements, specimens with a mean diameter of 46 mm and a nominal contact area of about 500 mm² were developed. Calculations presented in [4] have shown that the variation of the feed f_1 is appropriate to change the structure density *SD* characterising the size of the microstructured area referring to the nominal contact area. For this reason, two different feeds ($f_1 = 0.1$ mm and $f_1 = 0.3$ mm) were considered. The other parameters were kept constant at $f_2 = 0.03$ mm and $v_{c_1} = v_{c_2} = 200$ m/min. Finally, the unstructured reference specimens were machined using only one turning step without vibration assistance.

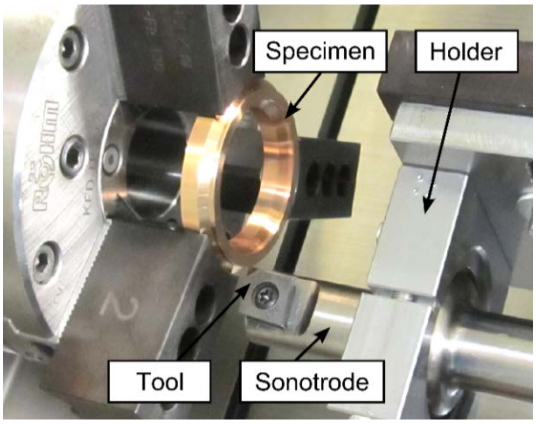
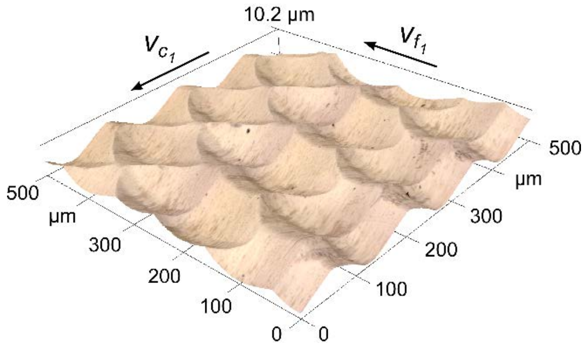


Figure 9 - Setup for the VAT experiments.

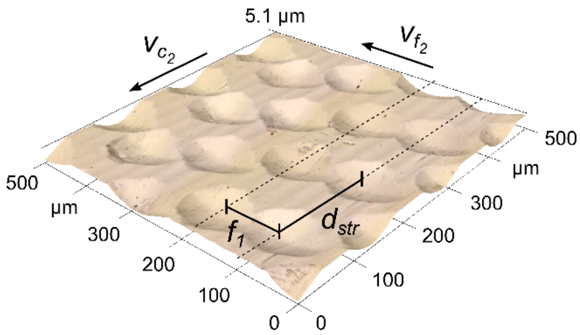
3.4 Experimental results

3.4.1 Surface microstructuring

Using a confocal 3D laser scanning microscope, the surface structure of the specimens after the machining steps was visualised and evaluated qualitatively. The images in Figure 10 illustrate that nearly burr-free microstructures with low surface roughness values were obtained with the machining procedure.



(a) Surface after the first machining step



(b) Surface after the second machining step

Figure 10 - Surface structures after the different machining steps, vertical axes superelevated by 500 %.

Geometric parameters characterising the arrangement of the microstructures are outlined in Figure 10b. As the distances of the lowest points of the structures in the feed direction are determined by f_1, the distances in the cutting direction depend on the vibration frequency and the cutting speed as follows:

$$d_{str} = \frac{v_{c_1}}{f_v}. \tag{4}$$

It has to be considered that the geometry of the microstructures is changed in addition to their arrangement by the vibration frequency and the cutting speed. Because of the constant frequency and cutting speed used, the calculated distance d_{str} was 139 µm in all experiments. Measurements yielded a higher value of (146 ± 2) µm because of a slightly lower resonance frequency of the ultrasonic system, yet revealing good compliance with the theoretical value. Using the calculation method introduced in [4], the depth-to-diameter ratio of the microstructures was specified with a value of approximately 0.05. Furthermore, the structure density amounts to 58 % for f_1 = 0.1 mm and 25 % for f_1 = 0.3 mm.

The machined area per time A_m/t_m and the number of microstructures per machining time n_{str}/t_m can be quantified for the parameter sets used with Equations (2) and (3). The calculated values in Table 2 illustrate that the surface microstructuring can be realised with low additional effort compared to the unstructured surface by the help of the vibration-assisted machining step.

Specimen	*A_m/t_m (mm²/s)*	*n_{str}/t_m (1/s)*
Unstructured	100.0	-
f_1 = 0.1 mm	76.9	5538
f_1 = 0.3 mm	90.9	2182

Table 2 - Parameters characterising the process efficiency.

3.4.2 Tribological measurements

For the tribological investigations a ring-on-disc setup (Figure 11) was applied. The sliding velocities were varied in the range of 0.05 m/s ≤ v ≤ 3 m/s and the normal forces F_N were set to 40 N and 220 N.

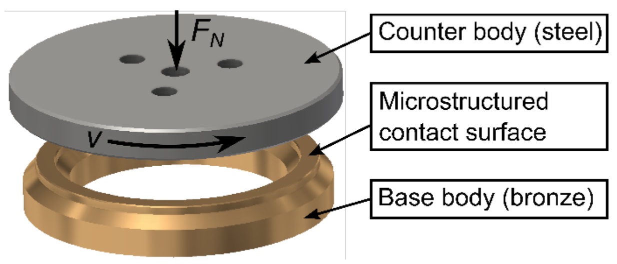
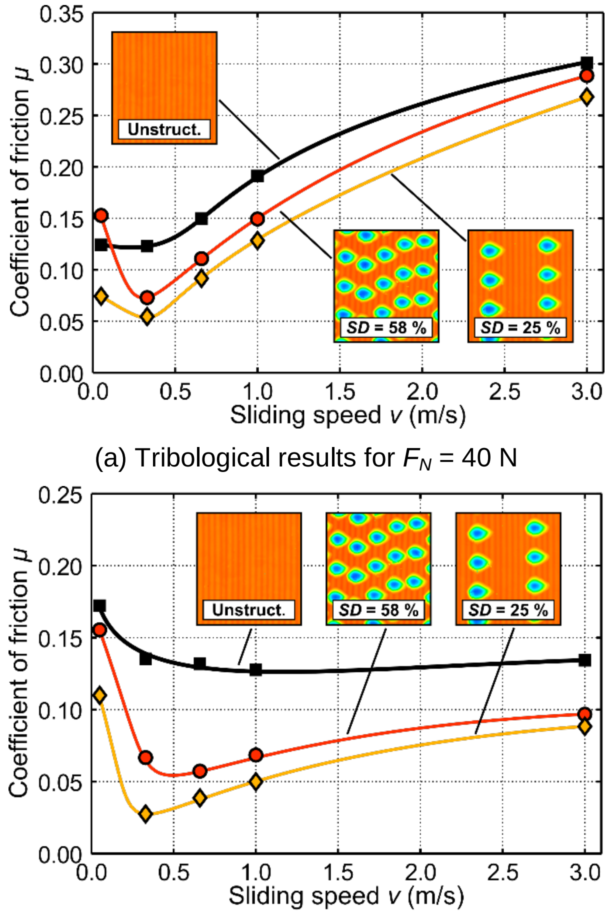


Figure 11 - Ring-on-disc test configuration.

The experiments were realised under immersion lubrication with the synthetic engine oil Castrol EDGE 5W-30 at a constant temperature of 60 °C. During the experiments, the friction moment was monitored. With these data the steady-state friction response was analysed.

The results of the measurements are presented in Figure 12. The coefficient of friction is plotted as a function of the sliding speed for both normal forces tested.



(a) Tribological results for F_N = 40 N

(b) Tribological results for F_N = 220 N

Figure 12 - Results of the tribological experiments.

Under a load of 40 N (Figure 11a) all specimens led to a coefficient of friction that increased significantly as the sliding speed was increased. At the higher load of 220 N (Figure 11b), the increase of the coefficient of friction in the hydrodynamic range was smaller compared to the results for the tests with the lower force. A minimum coefficient of friction that corresponds to mixed lubrication was observed at different sliding speeds in the range of 0.33 m/s ≤ v ≤ 1 m/s. For both loads, a significant reduction of friction was realised by the presence of the surface microstructures.

Concerning the surface structure, the higher feed f_1 leading to the structure density of 25 % resulted in the lowest coefficients of friction. Similar results using a steel-bronze assembly were also obtained by Koszela et al. [5]. A systematic analysis of the tribological mechanisms combined with the beneficial friction behaviour will be carried out more detailed in further investigations.

4 SUMMARY AND CONCLUSIONS

Two different technologies based on the turning process and using vibration assistance are presented. For sealing and bearing applications, a setup for twist-reduced turning is introduced. By using a short stroke actuator resulting in a start-stop turning kinematics surfaces with a zero lead structure can be generated. Consequently, this process enables the machining of surfaces which can be used as counterface for sealing rings. Furthermore, an improvement of the dynamic stability of the system allows a reduction of the machining time.

With the aim to produce microstructured surfaces for friction and wear reduction by turning, a second approach using vibration assistance was developed and evaluated experimentally. Based on different characteristic parameters it can be concluded that the two-stage process works efficiently. In comparison to the unstructured surface only a low additional effort is necessary to generate the microstructures. Tribological investigations are carried out using a ring-on-disc setup and different load cases. The results confirm the potential of the defined microstructures as an effective method for the reduction of friction.

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Implementation of a Multilateration Strategy for CNC Machine Calibration

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Abstract

Regular calibration of CNC machines and CMMs is required in order ensure high accuracy of machining processes. Typically calibration consists of two steps; physical measurements when the machine is taken out of production and processing of data with errors compensation. The ultimate goal is to carry out calibration in the shortest possible time in order to reduce the machine downtime. Multi-lateration with laser trackers is one of the latest techniques applied in industry. This paper presents the implementation of a sequential multi-lateration strategy based on the unconstrained optimization algorithm using the fitness function, which allows to minimize measurements errors for calibration of CNC machines.

Keywords

Multi-lateration, Interferometry, Calibration

1 INTRODUCTION

CNC machines and Coordinate Measuring Machines (CMMs) require regular calibrations in order to determine machine axes errors, rectify and/or compensate them. It is desired to have a calibration strategy that does not require long periods of time to set up and process the data. Calibration can be achieved using direct or indirect measurement methods. The use of a laser tracker and the principle of multi-lateration is an example of indirect measurement [1-11].

The calibration process is as follows. Multiple measurements are taken from different positions with a single laser tracker or with multiple fixed laser trackers. The laser tracker(s) measures the distance to the target, which is the Tool Centre Point (TCP). These data are then processed and optimised using a fitness function of Matlab. The generated error map is then applied to correct the theoretical kinematic model of a machine in order to calculate the required axis compensations for each particular point of the machine working envelop. The aim of this research is to implement a multi-lateration strategy for calibration of a CNC machine.

2 ERRORS OF THE CNC MACHINE AXIS

Various sources contribute to the inaccuracy of a machine, causing the actual position of the Tool Centre Point (TCP) to deviate from the desired coordinates while in operation.

Error sources can be divided into two categories, namely quasi-static error and dynamic error [6].

2.1 Quasi-static Error

Quasi-static error consists of geometric error, stiffness error and thermal error and is believed to contribute largely to the inaccuracy of the machine [6].

Geometric errors arise due to the assembly process and the tolerances assigned to each component during design.

Although care must be taken when assembling a CNC machine, misalignment and imperfections in the components are always present to some extent. A prismatic joint has a total of six parametric errors assigned to it, namely three rotational errors and three translational errors. These errors are illustrated in Figure 1. Stiffness errors arise from the elasticity of the mechanical components used in the system.

Thermal errors are induced by temperature variations and behave in a non-linear manner, thus making them difficult to estimate [6]. Quasi-static errors can, to some extent, be measured and compensated to improve on the accuracy of the machine. A kinematic model predicting the behavior of the machine allows for compensation of the TCP to improve on its accuracy.

2.2 Dynamic Error

According to Schwenke et al [6] dynamic errors are regarded as random and not systematic error. The relevance of that being that dynamic errors are considered to not be suitable for software compensation in offline mode. Dynamic errors arise from part movements and mechanical vibrations. Dynamic errors can be minimized by operating a CNC machine at lower speeds; however, this will result in longer cutting time and loss of productivity.

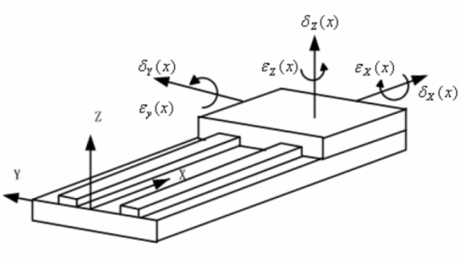

Figure 1 - Six Parametric Errors in a Prismatic Joint [6]

3 LASER INTERFEROMETRY

Laser interferometers, used for machine calibration, consist mainly of a light source (typically a HeNe laser), beam splitters, detector circuits and mirrors. Figure 2 illustrates a basic interferometer. A laser beam is directed towards a beam splitter, where the beam is separated into two similar beams. The one beam is directed towards a reference mirror with fixed separation, causing a reference signal to be obtained, while the second beam is directed towards the retro-reflector connected to the machine head during measurement.

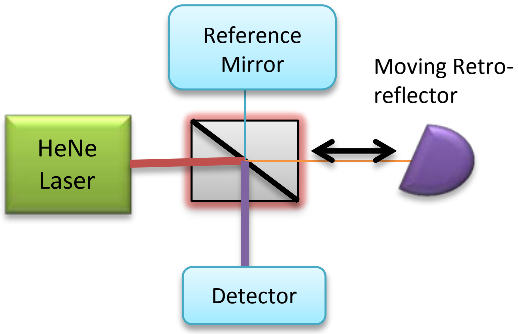

Figure 2 - Graphical Illustration of a Laser Interferometer

The signal returned from the retro-reflector combines with the reference signal on return and produces a resultant signal based on the superposition principle. As the retro-reflector moves, the separation between the beam splitter and the retro-reflector changes, causing interference between the reference signal and the measured signal. Constructive interference occurs when both the reference signal and the measured signal are in phase, while destructive interference occurs when the two signals are out of phase. The difference in wavelength between the two signals produces "fringes" (light and dark patterns) that can be interpreted by electrical circuits using photo diodes.

The detector circuit usually consists of two parts, achieved by splitting the resulting beam into two equal beams by means of a beam splitter. One of the beams are usually directed at a four quadrant photo-sensitive diode (PSD), which sends an electrical signal to the drive system to ensure that the laser beam is always directed at the retro-reflector (by means of a gimbal-mounted laser beam). The second beam is directed towards the fringe counter, which calculates the number of fringe changes. Knowing the number of fringes "n" and the wavelength "λ" of the laser beam, the change in distance (known as relative distance) can be calculated by the following formula:

$$Distance = n \times \lambda \qquad (1)$$

The accuracy of the interferometry measurement is therefore dependent on the wavelength of the laser beam.

Although laser interferometers are capable of production very accurate results, the measurement accuracy is limited by the encoder resolution which contributes significantly to the measurement uncertainty.

Recently a laser tracer has been introduced for machine calibration, which automatically follows the target reflector while continuously measuring the distance to the target [7-12]. The laser tracer uses a fixed, high precision, sphere as a reference reflector for the laser interferometer (Fig. 3). Therefore, no azimuth and elevation encoders are present in the laser tracer, but merely a stable centre of rotation.

Figure 3 - Etalon laser tracer [12]

4 METHODOLOGY

Multi-lateration was implemented by optimization of the measurement model, thus finding a set of values that satisfy the chosen tracer positions, obtained length information and target point coordinates.

The residual error between each of the target coordinates and tracer positions are given by the following equation [1]:

$$d_{ij}(L,P,T) = \sqrt{(X_i - x_j)^2 + (Y_i - y_j)^2 + (Z_i - z_j)^2} - L_{ij} \qquad (2)$$

Where Lij is the distance between the i^{th} target point and the j^{th} laser tracer.

Self-calibration of the system can be achieved by minimizing the error function [1]:

$$E(P,T) = \sum_{j=1}^{m} \sum_{i=1}^{n} {d_{ij}}^2(L,P,T) \qquad (3)$$

here m is the number of tracer positions and n is the number of target points measured for self-calibration. From equations (1) and (2) it can be observed that three parameters are present, namely: tracer position(s), target coordinate(s) and distance.

The distance information is obtained from the measurement, but uncertainty regarding the tracer position and target coordinates are still present. The G-Code strategy makes use of the theoretical target coordinates to approximate the position of the tracer by minimizing the error equation.

However, due to the error of the machine, the actual coordinates achieved by the TCP during measurement are likely to deviate from the theoretical G-Code coordinates; hence the length information would produce a "fix" on the tracer position that does not truly reflect the system. The updated target coordinates are determined from the calculated tracer positions, thus any inaccuracy in the tracer position will influence the final TCP coordinates. An unconstrained optimization approach is proposed that does not assume ideal target coordinates, but instead optimizes the entire model based on the obtained measurement values and the kinematic model of the machine only.

4.1 Unconstrained Optimization

As mentioned previously, three parameters are present in equation (3). By allowing the optimization algorithm to adjust both the tracer positions and target coordinates, a best-fit model would be obtained that satisfies equation (3). However, since no target coordinates or tracer positions were defined, the model will be unconstrained and able to translate and rotate freely in space. The unconstrained model can be seen in Figure 4.

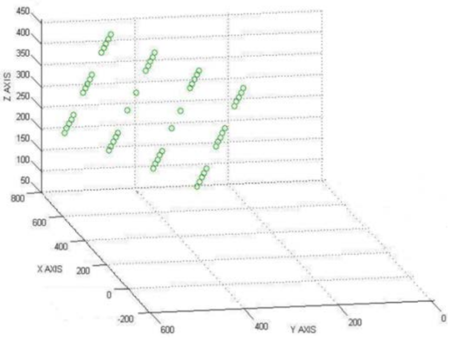

Figure 4 - Unconstrained Optimization Model

Basic transformation theory can be applied to correct the model. Mathematically the rotation and translation of a point P_0 (x, y, z) is given by:

$$P_0' = RP_0 = R_x R_y R_z T_x T_y T_z P_0 \quad (4)$$

Where P_0' is the reframed coordinates, P_0 is the initial coordinates. *Rx,y,z* are *Tx,y,z* are standard frame rotational and translational matrices.

The rotation/translation matrices that best mirror the initial model to the desired model specified by the G-Code strategy were obtained by using the optimisation algorithm. Hence, the reframed tracer positions can be calculated.

Six parametric errors associated with each linear carriage on a machine, as stated previously, include three translational errors and three rotational errors. Therefore, for a 3-axis CNC machine, there are 18 parametric errors for the axis as well as three orthogonal errors, resulting in a total of 21 errors, which are shown in Table 1.

Axis		X	Y	Z
Scale Error		$S_x(x)$	$S_y(y)$	$S_z(z)$
Straightness Error		$S_y(x)$, $S_z(x)$	$S_x(y)$, $S_z(y)$	$S_y(z)$, $S_x(z)$
Rotational Error	**Roll**	$\varepsilon_x(x)$	$\varepsilon_y(y)$	$\varepsilon_z(z)$
	Pitch	$\varepsilon_y(x)$	$\varepsilon_z(y)$	$\varepsilon_x(z)$
	Yaw	$\varepsilon_z(x)$	$\varepsilon_x(y)$	$\varepsilon_y(z)$

Table 1 - 21 Parametric Errors of a 3-axis System, [13]

Where [13]:

$$X_p = x + [S_x(x) + S_x(y) + S_x(z)] - y[\alpha_{xy} + \varepsilon_z(x)] - z[\alpha_{zx} - \varepsilon_y(x) - \varepsilon_y(y)] + x_t - y_t[\varepsilon_z(x) + \varepsilon_z(y) +_z(z)] + z_t[\varepsilon_y(x) + \varepsilon_y(y) + \varepsilon_y(z)] + \tau_x \quad (5)$$

$$Y_p = y + [S_y(x) + S_y(y) + S_y(z)] - z[\alpha_{zy} + \varepsilon_x(x) + \varepsilon_x(y)] + x_t[\varepsilon_z(x) + \varepsilon_z(y) +_z(z)] + y_t - z_t[\varepsilon_x(x) + \varepsilon_x(y) + \varepsilon_x(z)] + \tau_y \quad (6)$$

$$Z_p = z + [S_z(x) + S_z(y) + S_z(z)] - x[\varepsilon_y(x) + \varepsilon_y(y)] + y\varepsilon_x(x) - x_t[\varepsilon_y(x) + \varepsilon_y(y) +_y(z)] + y_t[\varepsilon_x(x) + \varepsilon_x(y) + \varepsilon_x(z)] + z_t + \tau_z \quad (7)$$

The kinematic model of the machine mathematically describes the position of the TCP with the effects of error. Therefore, since the locations of the laser tracer are known, as well as the length information, the kinematic model can be combined with the multi-lateration algorithm by adjusting the error parameters to predict the TCP coordinates. The predicted coordinates are then used as the target positions when calculating the fitness function using equation (1). The optimization algorithm (fminsearch function in Matlab) was applied to alter the error parameters until the model satisfied the laser tracer measurements and the laser tracer positions. The result being a kinematic model with calculated error parameters for each axis of the CNC machine. The kinematic model may now be used to predict TCP coordinates while continuously updating the error parameters if discrepancies exist between the predicted coordinate and the measured coordinate for each TCP location.

5 EXPERIMENTATION AND RESULTS

The multi-lateration technique was used to determine volumetric error of the machine tool, thus obtaining knowledge about the pitch, roll and yaw of the TCP. A bridge type CMM was used in the experiments, which represented a 3-axis CNC milling machine.

Sequential multi-lateration was chosen in the experiments using the LaserTRACER. In order to obtain representative measurement results for self-calibration and coordinate measurement in three dimensions, a minimum of four tracer positions are required. Therefore, the LaserTRACER was placed at four distinct positions and, at each position, measuring the distance between the TCP and tracer for the entire G-code strategy of the machine tool was measured.

Applying the transformation algorithm yielded the reframed Cartesian coordinates of the LaserTRACER positions, which are shown in Table 2, as well as the reframed measurement model, which is shown in Figure 5.

Tracer Position	X	Y	Z
1	701.2363	-70.6192	289.7376
2	139.0475	-92.2096	290.4094
3	415.4816	-397.4090	543.1603
4	410.1185	-162.0384	279.6796

Table 2 - Reframed Tracer Positions

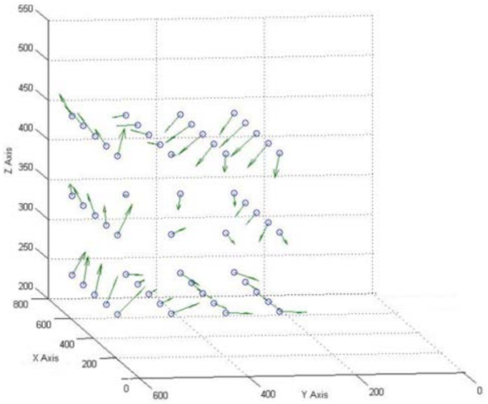

Figure 5 - Reframed Measurement Model

The vectors in Figure 5 provide an indication of the coordinate offsets at each target point. It is evident that the errors appear to be systematic. Hence, it can be concluded that the model was reframed successfully and produced Tracer Positions comparable to those obtained by other programs used previously by WZL.

The error parameters were then used to correct the CNC kinematic model and obtain the predicted TCP coordinates, which were then used as the target position when calculating the fitness function using equation (1). Figure 6 shows the results obtained from optimizing the error parameters of the kinematic model.

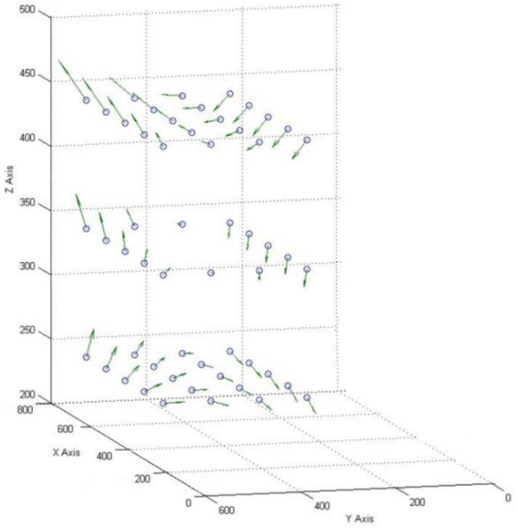

Figure 6 - Final Error Model of the CMM

By comparing Figures 5 and 6 it is evident that similarity exists between the coordinates measured using only LaserTRACER information and using TCP information of the CMM based on the kinematic model.

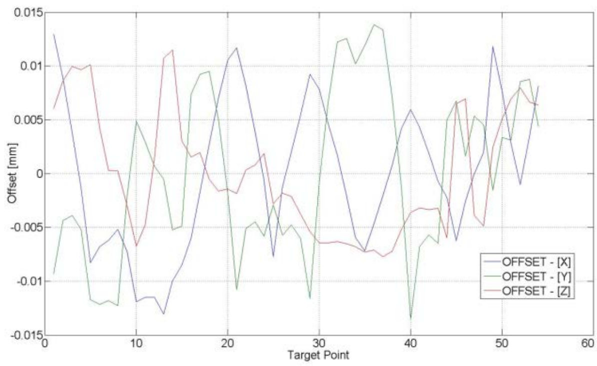

Figure 7 - Coordinates offsets

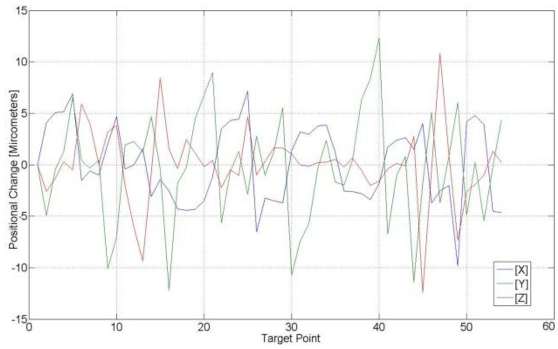

Figure 8 - Positional Change of Target Coordinates

The difference between the desired and the experimental results is further shown in Figure 7, while, the change in position between two consecutive points is shown in Figure 8.

6 CONCLUSIONS

This paper presents the implementation of a multi-lateration strategy to determine positional coordinates of a bridge type CMM using a laser tracer. Sequential multi-lateration was performed from four different tracer locations to obtain a set of measurements for offline processing.

The desired TCP trajectory was defined by the created G-Code strategy during measurement. Optimization of the input data yielded a model consisting of 4 tracer positions and 54 target coordinates. The obtained model was translated and rotated using mathematical manipulation to obtain a best-fit to the desired TCP trajectory. Combining the laser tracer measurements and the optimisation results allowed to determine the systematic error parameters and to correct the kinematic model of a 3-axis CNC machine accordingly.

The multi-lateration strategy described in this paper serves as a foundation for further research towards “on-the-fly” calibration of machine tools using interferometry.

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Communication in a LabVIEW Based Holonic Controller

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Abstract
This paper presents a communication approach for a holonic controller developed in LabVIEW. The controller is aimed at station that forms part of a reconfigurable assembly cell. The objective of the research was to evaluate the extent to which LabVIEW facilitates reconfigurability in this context. The holons were implemented by using LabVIEW's producer/consumer (to achieve asynchronous inter- and intra-holon communication) and state machine architectures. The paper discusses some implementation considerations. The paper shows that LabVIEW offers some attractive facilities for lower levels of reconfigurable control systems.

Keywords
LabVIEW; Reconfigurable manufacturing system; Holonic control system

1 INTRODUCTION

Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) is a platform and development environment for a visual programming language from National Instruments (NI). This paper evaluates LabVIEW as a platform for the control for a subsystem of a reconfigurable manufacturing system (RMS).

The motivation for considering LabVIEW is that other control approaches, such as agent-based control (which have been used in most RMS research) and IEC 61499 function blocks, have not found favour with industry. IEC 61131-3 languages, ubiquitous in manufacturing control, on the other hand, have not found application in RMS control systems, although Hoffmann [1][2] has presented some work in this regard. LabVIEW is considered here because it has been used with success for test equipment in manufacturing environments and also for major scientific projects, such as the control of the South African Large Telescope (SALT). LabVIEW runs on mature and reliable hardware and there is a substantial user base, in particular at universities and research institutions. People that are not skilled in high-level programming can use LabVIEW and this is significant in manufacturing environments, that the authors are familiar with, where technicians are rarely skilled in object orientated programming and even less so in agent-based programming,.

LabVIEW is commonly used for data acquisition, instrument control and industrial automation [3]. LabVIEW programs or subroutines are called Virtual Instruments (VIs), because their appearance and operation imitate physical instruments such as oscilloscopes and multi-meters [3]. Each VI has three components: a block diagram, a front panel and a connector pane. The connector pane is used to represent the VI in the block diagrams of other calling VIs. The front panel is built with controls and indicators, which are the interactive input and output terminals of the VI, respectively [4]. Therefore, controls and indicators on the front panel allow an operator to input data into or extract data from a running VI. It is worthwhile to note that the front panel also serves as a programmatic interface. After the front panel has been built, graphical representation is used to add code to control the front panel objects. The block diagram contains this graphical source code [4].

An RMS is a responsive manufacturing system, which includes that its production capacity is adjustable to fluctuations in product demand and its functionality is adaptable to new products [5]. RMSs are ideally flexible (able to manufacture a limited family of products in a given configuration), convertible (amenable to adding or removing subsystems in a reasonably short time), scalable (able to adapt to changes in production volumes required by the market), modular (in its hardware and control), integrable (the interfaces between modules are amenable to easy integration) and diagnosable (able to detect fault conditions). These key characteristics help achieve the desired reduction in reconfiguration time and cost [5]. The goal in implementing an RMS is to be able to cope with rapid, unpredictable changes in production requirements through reconfiguration [6].

RMS control systems are widely implemented using holonic control architectures since these architectures offer good modularity and integrability in the control system. The relevant modules in the control system are also directly associated with hardware modules, thereby simplifying the mapping of the hardware to reconfiguration to the control system. Product-Resource-Order-Staff Architecture (PROSA) [7], one of the best known reference architectures for holonic control, was chosen for the research presented here.

The research presented in this paper contributes to an evaluation of LabVIEW's ability to facilitate reconfigurability within the context of the controller for a station inside a manufacturing cell. The evaluation used a rivet feeder station as a case study. This station is part of the RMS cell being developed at the Mechatronics, Automation and Design Research Group at Stellenbosch University. The rivet feeder station includes a vibratory bowl feeder, a singulation device, a pick-n-place mechanism and an XYZ positioning table (Figure 1). More details about the case study are given in [8].

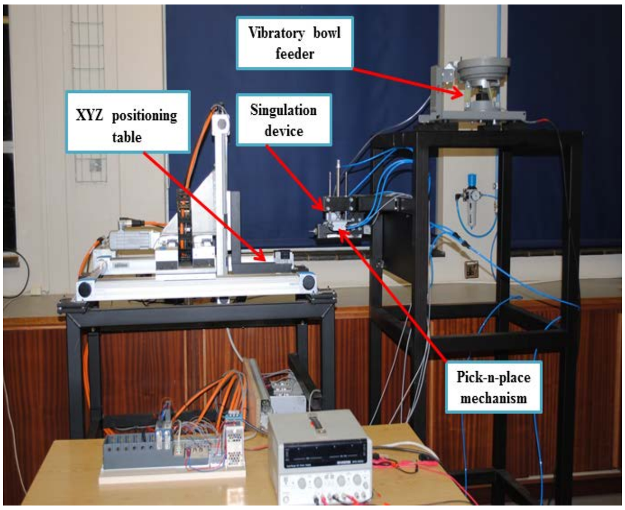

Figure 1 - Rivet feeder station hardware

2 CONTROLLER ARCHITECTURE

2.1 Station controller

PROSA was selected as reference architecture since reconfigurability is enhanced by PROSA's high degree of self-similarity, which reduces the complexity to integrate new components and enables easy reconfiguration of the system [7].

In PROSA, a product holon holds the process and product knowledge required for the correct manufacturing of a particular product type. The product holon acts as an information server to the other holons in the holonic manufacturing system [7]. A resource holon contains a physical part (a production resource) of the manufacturing system, as well as an information processing part that controls the resource. A resource holon offers production capacity and functionality to the surrounding holons and can be seen as an abstraction of the production means such as a factory, a shop, machines, furnaces, conveyors, pipelines, pallets, etc [7]. An order holon represents a task in the manufacturing system. It is responsible for performing the assigned work correctly and on time [7]. The staff holons assist the aforementioned basic holons in performing their work and can reduce the work load and work complexity of the basic holons, by providing them with expert knowledge [7].

Figure 2 shows the architecture of the LabVIEW based controller, consisting of six holons, i.e. coms holon, request manager holon, order holon, product holon manager, pick-n-place holon and XYZ table holon. The coms holon and the request manager holon are staff holons, while the XYZ table holon and the pick-n-place holon are resource holons. The station controller, in its present form, makes provision for only one order holon and all the product holons are represented by a single product holon manager.

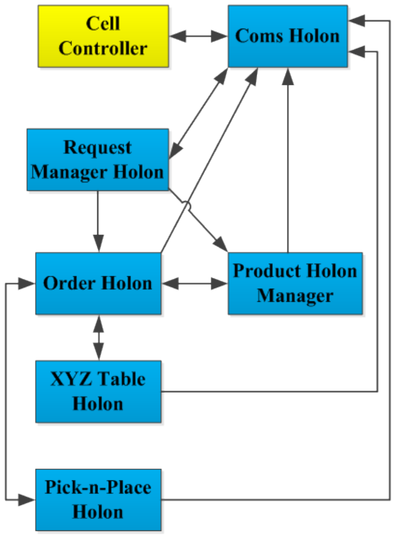

Figure 2 - Rivet feeder station control architecture

2.2 Common holon internal architecture

Each holon must be able to run independently from other holons. Therefore each holon was implemented in LabVIEW using a while-loop containing all its functions. This while-loop terminates only when the command to shut down is communicated through a notifier.

The intelligent decision-making algorithms of the holons were implemented using LabVIEW's state machine architecture [9]. The state machine associated with each holon is implemented as a case structure inside the holon's main while-loop. The holon's main while-loop, which repeats the code within its subdiagram until a stop condition occurs, executes the case structure and uses the case selector to effect transition to the appropriate case. Each case of the case structure corresponds to a state of the state machine and the case structure's shift registers are used to pass data from one state to the next state.

Further details of the holon implementation are given by [8].

3 INTER-HOLON COMMUNICATION

3.1 Requirements

Holons have the ability to act independently, but also to collaborate to achieve common objectives. Communication between holons is therefore a critical function.

Inter-holon communication is inherently asynchronous since one of the key aspects of a holonic system is that each holon can operate independently, but also collaborate with other holons to achieve a common objective. Each holon should therefore be able to receive a message from one holon and keep it in a message queue, whilst communicating with another holon or performing other tasks. Furthermore, asynchronous communication is necessary so that the sending holon's execution is not blocked while waiting until the receiver is ready to process the message.

LabVIEW automatically divides applications into multiple threads [10], but this is not apparent to the users or programmers. To allow multithreaded operation, all holon interconnections (i.e. the inter-holon communication) has to be compatible with running each holon in its own thread.

3.2 Implementation

Various LabVIEW methods for transferring data between VIs can be considered for inter-holon and intra-holon communication. The method used in each situation depended on the continuity of data, the need for a buffer, the number of variables to be passed and the type of data to be shared [11].

One form of inter-holon communication was already mentioned in Section 2.2: notifiers were used for simple communication actions employing Boolean values such as the occurrence of error conditions and shut-down notifications [8]. The coms holon is, in addition to the external communication discussed below, responsible for stopping the station controller when an error occurs or when the operator hits the *stop* button. To achieve this, *Notifier operations*, found under the Synchronization palette in LabVIEW were used. The coms holon uses the *Send Notification.vi* to send a *true* Boolean value as a notification to other holons. The other holons receive the notification via the *Get Notifier Status.vi*. By wiring the notification terminal of each holon to the conditional terminal of the holon's while-loop, the station can be shut down.

More complex inter-holon communication was implemented using LabVIEW's queues and third-party LabVIEW XML functions for constructing and parsing messages. Asynchronous communication using queues is based on LabVIEW's producer/consumer architecture [9].

With the producer/consumer architecture, one holon can send (produce) messages to other holons (consumers). The queues acted as FIFO message buffers for inter-holon communication (and in some cases for intra-holon communication). LabVIEW provides convenient functions to add a message (here in the form of XML strings) to a queue, to remove the oldest message, to view the oldest message without removing it from the queue and to check whether there are any messages in the queue. LabVIEW queues can trigger a timeout if a message is not available within a set time, which is a useful feature for diagnosability.

LabVIEW queues therefore allow lossless asynchronous communication between holons, where the sending holon adds messages to the queue and the receiving holon removes the messages when it is ready to do so.

Only one queue could have been used as "inbox" for each holon for inter-holon communication. However, multiple queues were implemented (one queue for each sender-receiver pair) since it obviates the need to read the received message in order to tell which holon sent it. Furthermore, using multiple queues simplifies prioritising the messages, allowing a holon to get the information it needs most urgently without having to first read the other, earlier messages in a queue. Finally, using multiple queues aids in debugging and controller reconfiguration by clearly defining in the architecture where messages come from and go to in each queue. In the implementation here, the queue names were composed of the sending and receiving holons' names, e.g. "ProductInfoReq_from_OH_to_PHM".

Since each LabVIEW queue handles only one data type, all the messages passed through the queues were here formulated as strings in XML format. For the sake of commonality, the XML conversion VIs that were selected for the external communication (described in a later section) was also used for the internal communication.

4 INTRA-HOLON COMMUNICATION

Intra-holon communication is required when holons internally have separate processes running in parallel or sequentially, and these processes have to exchange information.

This intra-holon communication was achieved using

- Queues (similar to inter-holon communication),
- Local variables (for static information)
- By passing data through wires, which are flow paths connecting different function nodes on the block diagram, and
- By shift registers, as mentioned in Section 2.2, where information needs to be passed from one state to a subsequent one.

5 EXTERNAL COMMUNICATION

The station controller must also be able to communicate with the cell controller. In the research presented here, XML strings passed over TCP/IP connections were chosen for this type of communication since it is vendor-neutral and allows communication between controllers implemented on various technology platforms (e.g. C# and LabVIEW). The XML format was also chosen since it naturally makes provision for information that can be used to improve the robustness of the information exchange.

LabVIEW's built-in XML functions could not be used for the messages exchanged with the cell controller, because some of the XML functions cannot generate or parse XML schemas defined by others, while other functions are unsuitable because of complexity in their use. Therefore, the third-party JKI EasyXML palettes were used to convert LabVIEW data to and from XML strings. These functions were used for both external communication (with the cell controller) and inter-holon communication, to keep the XML schemas consistent.

JKI EasyXML is a LabVIEW toolkit that can be used to create, parse, read, and write LabVIEW data to and from XML [12] and, unlike the built-in LabVIEW XML functions, allows the user to control the XML item names. "Easy Generate XML_JKI EasyXML.vi" and "Easy Parse XML_JKI Easy XML.vi." respectively serialise (on the sender's side) and de-serialise (on the receiver's side) LabVIEW data structures, by converting the LabVIEW data names (labels) to/from XML item names and the LabVIEW data values to/from XML item values. In order to convert the output to the desired data type after parsing, the LabVIEW function *variant to data* is used.

The coms holon, one of the staff holons, handles communication between the station controller and the cell controller. The cell controller sees the station controller as a single module and therefore one holon in the station controller should handle all the communication with the cell controller. Using a separate coms holon also shields the cell controller communication from delays when the other holons are busy, and vice versa. The role fulfilled by the coms holon can be expected to be present in all station controllers that are modules in a distributed control system. However, the protocol used for information exchange between the cell controller and the station controller could take various forms and therefore what is presented here in this respect, should be seen as an illustrative example.

The coms holon maintains two FIFO buffers, the *IN FIFO* and the *OUT FIFO*, in respective while-loops, namely a reader and a writer. The *IN FIFO* that holds messages from the cell controller and the *OUT FIFO* that holds messages to be sent to the cell controller, as illustrated by the flow charts in Figure 3.

The buffer of the TCP/IP socket that receives messages from the cell controller (implemented using a standard LabVIEW method) was used as the *IN FIFO*, while the *OUT FIFO* queue was implemented using the queue functions as with other inter-holon communication. The other holons place their messages for the cell controller in the *OUT FIFO* queue.

The cell controller and station controller communicate through TCP/IP with messages formatted as XML strings. Using the *TCP Read* VI, the coms holon first reads four bytes of data from a TCP/IP connection, which gives the length of the message, and then reads the indicated number of bytes. Similarly, the coms holon uses the *TCP Write* VI to write data from the rivet feeder station controller to a TCP/IP connection with the cell controller.

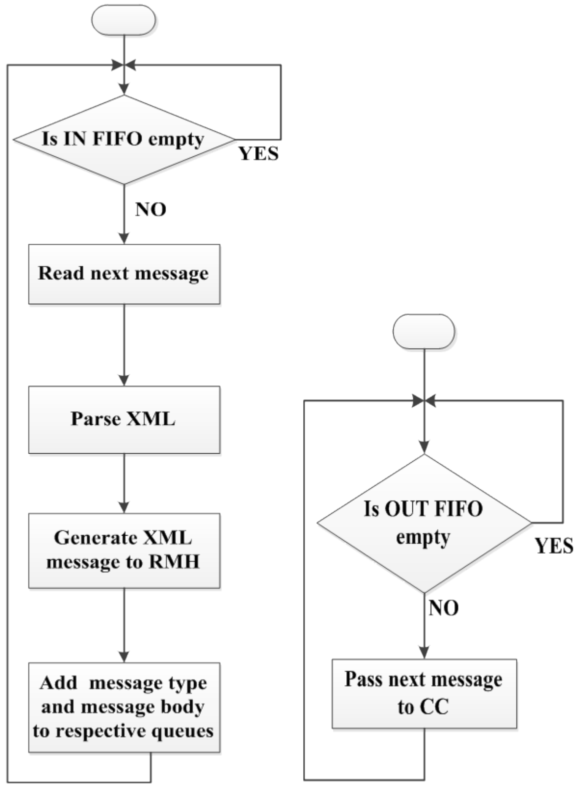

Figure 3 - Coms holon flow-charts

The coms holon is also responsible for stopping the station controller when an error occurs or when the operator hits the *stop* button. To achieve this, *Notifier operations*, found under the Synchronization palette in LabVIEW were used. The coms holon uses the *Send Notification.vi* to send a *true* Boolean value as a notification to other holons. The other holons receive the notification via the *Get Notifier Status.vi*. By wiring the notification terminal of each holon to the conditional terminal of the holon's while-loop, the station can be shut down.

6 COMMUNICATION WITH PHYSICAL DEVICES

LabVIEW's ability to interface easily with a wide range of National Instruments (NI) products, is a distinct advantage in using LabVIEW for a station controller. NI products allow the control program to run on a PC and also on stand-alone controllers, such as the compactRIO-9068 (cRIO-9068) used for the case study here. This 8-slot integrated controller and chassis system provided an interface between the LabVIEW based controller and the rivet feeder station resources, i.e. the Pick-n-Place mechanism and the XYZ positioning table. The controller used various digital inputs and outputs, operating at the popular 24 V level, to sense proximity sensors and to actuate pneumatic control valves. The case study also used a CANopen module to interface the controller with the Festo servo drives of the XYZ positioning table. Further details of the case study implementation are given in [8].

7 ASSESSMENT

Since the focus of this paper is a station in an RMS cell, an assessment was performed to determine to what extent the key characteristics of RMSs (flexibility, scalability, convertibility, modularity, integrability and diagnosability, as mentioned in Section 1) are demonstrated by the LabVIEW-based controller. The assessment was performed by carrying out experiments using the case study and by considering relevant LabVIEW features. Due to paper length constraints, the details of the assessment are given by [8] and the assessments are only briefly described here.

7.1 Changing the product type

In the first experiment, the impact of a change in product was tested. The experiment showed that introducing a new product, that does not require any new processes, required no changes in the station controller and hardware. The new product type could be accommodated without any station controller changes since the station controller is not limited to pre-programmed product types and the relevant production information was similar to the product family considered when designing the station.

7.2 Adding a new device to the station

Convertibility and scalability, the distinguishing features of RMSs, require the ability to reconfigure a manufacturing system so that new production technologies can be incorporated, new product types can be produced and the system's production capacity can be changed. Convertibility and scalability rely on modularity and integrability, also in the control system.

Therefore, it was important to assess the LabVIEW-based controller's convertibility and scalability, and this was done by adding a new functional element to the rivet placing station. In the controller, the reconfiguration led to the addition of a new resource holon, the singulation unit holon, and to changes to the order holon.

The addition of the new singulation unit holon and the changes to the order holon, including establishing the interfaces with the digital outputs to the solenoid valve, took about three and a half hours to complete.

7.3 Diagnosability

Diagnosability can play various roles, including warning higher level control systems when inconsistent production instructions are received or when a fault has occurred in the station resulting in its unavailability for production.

Faults in the station are diagnosed in the case study by checking for timeouts while waiting for operations (e.g. movement by the XYZ table holon) to be completed. In LabVIEW, timeout checking is easily performed by specifying the time, in milliseconds, that the function waits for an element (information) to become available in a queue. When a timeout occurs, LabVIEW activates a particular execution path and it is relatively simple to direct the holon to an error state, where a message to the cell controller can be generated and the station controller commanded to shut down.

In the third experiment, this ability to generate timeout errors was confirmed by deliberately setting an unreasonably short timeout for one action and confirming that an error message was sent to the cell controller, that an error message was also displayed to the operator and that the station was triggered to stop.

8 CONCLUSION

This paper contributes to the RMS research by evaluating the suitability of LabVIEW's communication functions for developing a controller for a reconfigurable manufacturing station. The paper shows that a holonic control architecture can be implemented to achieve reconfigurability of the rivet feeder station.

LabVIEW's communication functions hold the following advantages:

- LabVIEW's queues provide a convenient way to implement lossless asynchronous complex communication.
- Network-published variables and TCP/IP components simplify communication over a network, allowing easy distribution of parts of the controller.
- Third party methods are available to work with custom XML formats in LabVIEW.
- LabVIEW can easily communicate with hardware, such as digital I/Os, real time controllers (such as the compactRIO) and the main industrial communication protocols (such as the CANopen card used in the case study).

Reconfigurability assessments conducted on the case study showed that the key characteristics of RMSs were demonstrated. We therefore conclude that LabVIEW is suitable for implementing a station's control system in a reconfigurable manufacturing cell.

9 ACKNOWLEDGEMENTS

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11 BIOGRAPHY

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Titanium-Nickel Alloys for Bone Tissue Engineering Application via Cold Spray

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Abstract
Titanium-Nickel (TiNi) alloys are prospective materials for bone-tissue engineering because of their unique properties. Studies show that the current method widely used to manufacture TiNi alloys is powder metallurgy. But, this method has challenges of high costs, oxidisation of sensitive materials, and inability to fabricate thin porous coatings on thin surfaces with complex geometries. Cold spray (CS), a state-of-the-art additive manufacturing technology, can fabricate coatings at low cost and without deleterious effects on the materials. This technology fabricates metals/alloys and composites using a compressed-preheated supersonic-gas-stream mixed with feedstock powders. A research to establish the suitability of CS to fabricate TiNi alloys for bone tissue engineering was undertaken at Wits University in which TiNi alloy of equiatomic composition was coated via CS using optimised process parameters. The resultant specimens were examined and the results showed that CS technology can be used to fabricate TiNi alloys suitable for bone-tissue engineering application.

Keywords
Competitive Manufacturing, Bone Implants, Tissue Engineering, Cold Spray, and Titanium-Nickel alloy.

1 INTRODUCTION

Worldwide, the demand for bone implants has increased due to rising incidences of bone disorders caused by aging, growing number of diseases, and traffic related accidents [1]. Bones are part of the skeletal systems and their repair or replacement using bone implants is vital for supporting the body, allowing locomotion, and protecting organs. To perform these functions, the bones or their replacement must have: porosity of 30-60 %, tensile strength of 3.7-140 MPa, Young's Modulus of 0.16-18.1 GPa, and microhardness of 45-200 Hv [2], [3], [4], [5]. To restore degraded bones using bone implants, a multi-disciplinary research platform called Bone Tissue Engineering (BTE) was developed [6],[7]. From this platform, the Titanium-Nickel (TiNi) alloys emerged as prospective materials for bone implants due to their high corrosion resistance, high specific strength, low elastic modulus, super-elasticity, and high microhardness [8]. Further, studies established that the porous topography of the bone implants is an important requirement for bone in-growth, cell attachment and reduction of Young's modulus [9], [10].

Competitive manufacturing (CM) could be a solution for cheaper bone implants. CM is defined as the degree to which a firm produces goods that meet functional and market requirements, at lower costs while making profits [11], [12], [13]. In the case of bone implants, CM involves the alignment of manufacturing strategy with respect to specific cost competencies, quality, delivery, and flexibility that are necessary to achieve the competitive priorities in the healthcare services [13], [14], [15]. It is believed that through CM, it will be possible for the surgeons to use custom made implants instead of choosing only those that are close to the patients' requirements [16].

2 PROCESSES FOR MANUFACTURING OF BONE IMPLANTS

2.1 Powder metallurgy based processes

Conventional sintering, shown in Figure 1, is one of the widely applied powder metallurgy (P/M) based process for manufacturing bone implants. In this process, the feedstock powders are mixed, followed by compaction under high pressure, and finally sintered. The sintering operation is a high temperature/pressure treatment process that causes the powder particles to bond to each other with minor change to the particle shape, which also allows porosity formation in the product when the temperature is well regulated [17]. Another P/M based process is the Self-Propagating High Temperature Synthesis (SHS), shown in Figure 2, whose steps include mixing of reagents, followed by cold compaction, and finally ignition to initiate a spontaneous self-sustaining exothermic reaction to create the porous structures [18].

Although these P/M processes are mature technologies for fabrication of bone implants [17] they have difficulties of fabricating porous coatings on surfaces that are delicate or with complex geometries. In addition, these processes tend to produce brittle products because of cracks and oxides formed inside the materials. Further, the high costs and poor workability associated with these P/M processes restrict their application in commercial production of bone implants [6]. Consequently, new methods, based on additive manufacturing principles were developed [19], [20].

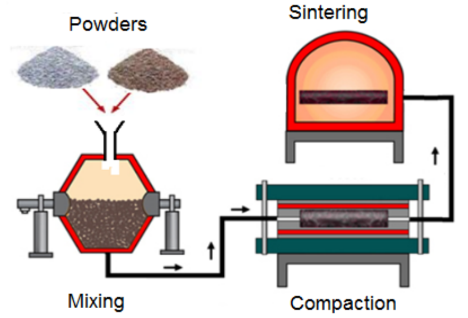


Figure 1- Powder metallurgy process

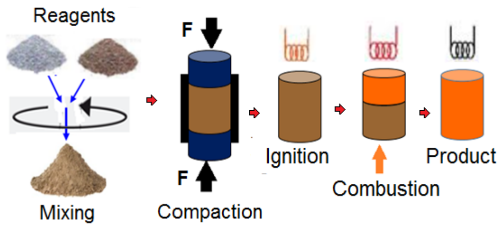


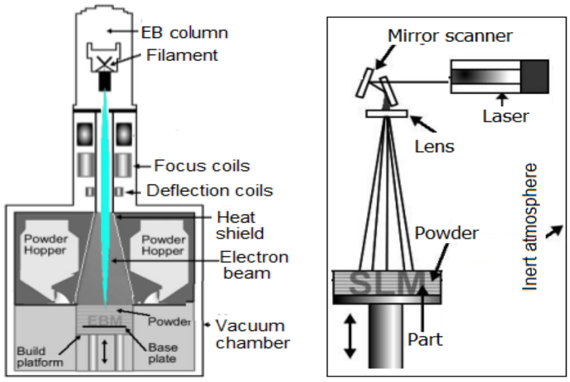
Figure 2- SHS process

2.2 Additive manufacturing processes

Electron Beam Melting (EBM), shown in Figure 3(a), is one of the additive manufacturing processes which fabricated Ti coatings by melting and deposition of metal powder, layer-by-layer, using a magnetically directed electron beam (EB) [20]. Though this method was proved to be successful, it has high set-up costs due to the requirement of high vacuum atmosphere.

Selective Laser Melting (SLM), shown in Figure 3 (b), is the second additive manufacturing method for Ti alloy coatings which completely melt the powder using a high-power laser beam. Similarly, this method is costly because it requires advanced high rate cooling systems. Moreover, the fluctuations of temperatures during processing negatively affect the quality of the products [6], [20].

In addition, EB and SLM were proved to have some disadvantages during the manufacturing of porous coating of Ti alloy bone implants due to: inhomogeneous properties, oxidation, cracks, high residual stresses, and brittleness of products [19], [21], [22]. Consequently, to address some of the above limitations, cold spray process was proposed to be used for fabrication of porous coatings on surfaces of bone implants [23], [24].



(a) (b)

Figure 3- Schematics for: (a) EBM and (b) SLM [20]

2.3 The cold cpray (CS) process

CS, shown in Figure 4, is the newest surface coating process which deposits metals, alloys or composite powders on a metallic or dielectric substrate using a high velocity (300 to 1200 m/s) jet of small (5 µm to 50 µm) particles injected in a stream of preheated and compressed gas passing through a specially designed nozzle [25]. This deposition process, which normally takes place at a temperature far below the fusion point of most feedstock powers, result in coatings with advantages such as minimal oxidation, high reproducibility, high flexibility, rapid deposition, and lower costs [25].

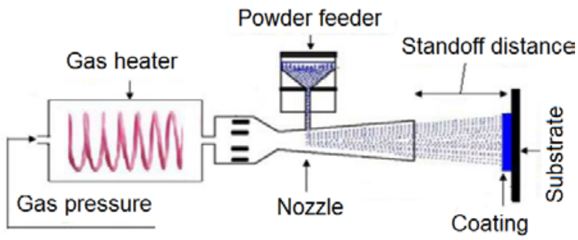


Figure 4- Schematic of CS process

Subsequently, various studies were carried out to establish how CS can deposit Ti, and TiNi powders. In this respect, Zahiri (2009), focused on the elimination of porosity in Ti coatings, and established that the temperature and pressure of the gas, and the standoff distance had predominant influence on the porosity of the coatings [23]. In another study, [26] prepared Ti:Ni (50:50 % at.wt) feedstock powder by mechanically milling the elemental Ti and Ni powders for 36-312 hours in the ball mill, in which the ratio of the mass of the powder to mass of the mixing balls, also called powder-to-ball mass ratio (PBR), was 1:8. The resultant powders were sprayed using air as the accelerating gas at a pressure of 2.7 Mpa, temperature of about 510^0C and the stand-off distance of 30 mm. It was discovered that the deposition of the feedstock powder was low due excessive strain hardening caused by longer milling times [26]. Later, Zhou (2010) prepared similar feedstock powder by milling

Ti:Ni (50:50 % at.wt) for 4-14 hours using a planetary ball mill with PBR of 1:28 at a rotation speed of 180 rpm. The resultant powders were deposited using helium gas, compressed at a pressure of 2.0-2.5 MPa, and preheated to 420-580^{0}C, and a standoff distance of 20 mm. It was observed that the thickness of the coatings fabricated using TiNi powders which were milled for longer times were reduced. This is because during deposition the particles in these powders partially melted and splashed away which effectively lowered the deposition efficiency [27].

From the above brief review, it appears that further investigations are required to establish the capability of CS in the deposition of TiNi alloys. Consequently, the main goal of this paper is to investigate the compatibility of the Ti:Ni (50:50 % at.wt) coatings, fabricated using CS, for bone implants through characterisation for porosity, microhardness, microstructure and stress-strain behaviour.

3 EXPERIMENTAL PART

3.1 Materials and equipment

Ti (SST-T5001), Ni (SST-N5001), Aluminium-Alumina (SST-0050) and Alumina (SST-G0002) powders were sourced from CenterLine (Windsor) Limited, Canada. The equipment used to characterise the powders and the coatings were: Field Emission Scanning Electron Microscope (FESEM)-Carl Zeis ∑IGMA equipped with Oxford X-act EDS detector, Microhardness Tester FM-700, Struers Automatic Polishing Machine and Optical Microscope (LEICA CTR 6000). A planetary ball mill, model Retsch PM400 MA, was used to mix the powders. A Low-pressure CS facility SST series P, purchased from CenterLine (Windsor) Limited, Canada, was used to deposit the powders. The tensile testing was carried using the tensile testing machine Shimadzu Autograph AG-20kN/50kNIC.

3.2 Powder preparation

The as received Ti and Ni powders were characterised for morphology using FESEM. The powders were then weighed such that the atomic weight ratio for Ti:Ni was 50:50 %. Then, the powders were mechanically mixed by cautiously adjusting the mixing parameters within the following limits: rotational speed between 200 RPM and 300 RPM, mixing time between 15 minutes to 120 minutes, and PBR between 1:1 and 1:3. In each case, the powder was milled for 15 minutes and then the samples were observed under an Optical Microscope. Optimal conditions were attained when a homogeneous mixture of powders was obtained with un-deformed and un-agglomerated particles.

3.3 Coating process

The values for processing parameters, namely: gas temperature (T), gas pressure (P), and standoff distance (S) were calculated using the Central Composite Design of Experiments (CCDOE) and equation (1), in which the coded levels, X_i = 1.682; -1; 0; +1; and 1.682, were obtained from the response surface shown in Figure 5 [28], [29]. X_{max} and X_{min} were the upper and lower limits of the CS machine specified in [30].

$$X_i = 1.682[2X - (X_{\max} + X_{\min})]/[X_{\max} - X_{\min}] \quad (1)$$

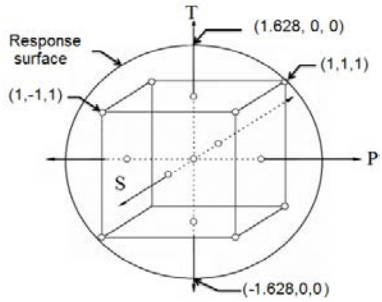


Figure 5- Response surface

In order to characterise the porosity, microstructure and microhardness, TiNi powder was cold sprayed on 20 x 20 x 3 mm mild steel substrates. For tensile testing, TiNi powder was cold sprayed on Copper (Cu) substrates machined according to ASTM E-8/E8M-11 standard. Aluminium-Alumina powder was initially coated between the Cu substrate and TiNi powder to assist in delamination of the coatings. Prior to coating, all the substrates were activated by grit blasting using Alumina powder. Air was used as process gas. During deposition process, the spray gun was manipulated automatically using a robot. To delaminate the TiNi coating from the Cu substrates, the specimens were immersed in 50% dilute Hydrochloric acid for 30 minutes.

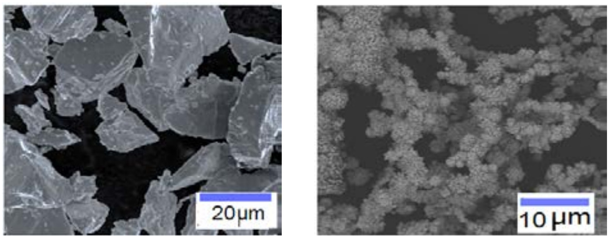
3.4 Coating characterisation

The TiNi coatings fabricated on mild steel substrates were sectioned, mounted and metallographically polished and characterised for microhardness, microstructures, and porosity.

The TiNi coatings fabricated on Cu substrates were tested for stress-strain behaviour. During this test the specimens were subjected to tensile load until they yielded and fractured, and a force-extension report for each specimen was obtained at the end of each test. Using the force-extension report and the measured cross-section area of the specimen, the stress and strain values were calculated, and a stress-strain curve for TiNi alloy was plotted from which the Young's Modulus and tensile strength were approximated. In addition, the graphs for variation of porosity and microhardness with spray parameters were plotted and are shown in the next section..

4 RESULTS AND DISCUSSIONS

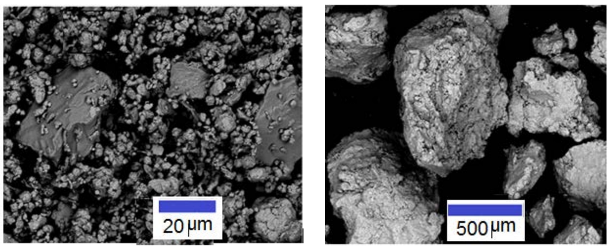
The morphology of as received elemental Ti and Ni powders are shown in Figure 6. As seen from Figure 6(a), the Ti powder have angular morphology, whereas Ni powder, shown in Figure 6(b), exhibits loose agglomeration of near- spherical particles .



(a) (b)

Figure 6 - (a) Ti and (b) Ni powder

Also, the optimum mixing parameters for the Ti and Ni powders were: rotational speed = 250 RPM, mixing time = 30 minutes, and PBR = 1:1. The resultant mixed TiNi powder was homogeneous with un-deformed and un-agglomerated particles as shown in Figure 7(a). This powder was favourable for CS process. In addition, these mixing parameters had less severe impact on the TiNi powder compared to those reported in [26], [27]. On the contrary, the mixing parameters of: rotational speed = 300 RPM, mixing time = 120 minutes, and PBR = 1:3, severely deformed and agglomerated the particles, as depicted in Figure 7(b). These particles unfavourable for CS process [31].



(a) (b)

Figure 7 - TiNi powder milled under: (a) optimal parameters, (b) severe conditions

Further, the calculated process parameters using the CCDOE, the measured microhardness and percentage (%) porosity values for selected experiments are summarised in Table 1.

Expts.	Spray parameters			Micro-hardness (Hv)	% Porosity
	T	P	S		
1	509	0.75	14	214	7.9
2	509	0.9	14	290	2.4
3	550	0.9	14	367	1.4
4	550	0.82	20	286	29.0
5	509	0.9	26	292	7.0

Table 1- Process parameters, microhardness and percentage (%) porosity

Furthermore, the graphs for process parameters, percentage porosity, and microhardness values shown in Table 1 were plotted. For example, Figure 8 is the graph for variation of percentage porosity and microhardness with the gas temperature. From this graph, it can be seen that as the gas temperature increase, the microhardness increase as well, while the % porosity of TiNi coating reduces.

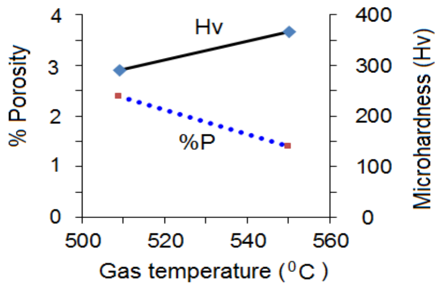


Figure 8- Variation of percentage (%) porosity and microhardness with gas temperature

Similarly, an increase in gas pressure led to the increase in microhardness, and reduction of percentage porosity of TiNi coatings, as illustrated in Figure 9.

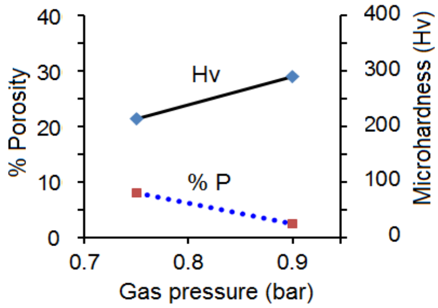


Figure 9 - Variation of percentage (%) porosity and microhardness with gas pressure

Further, Figure 10 indicates that an increase in the standoff distance leads to a rapid increase in percentage porosity while the microhardness of the TiNi coating reduces. In general, the results shown in Figure 8, Figure 9 and Figure 10 are in total agreement with the observations made by [23].

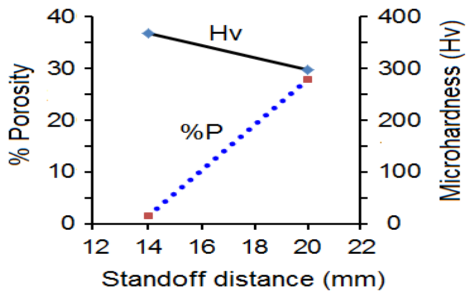
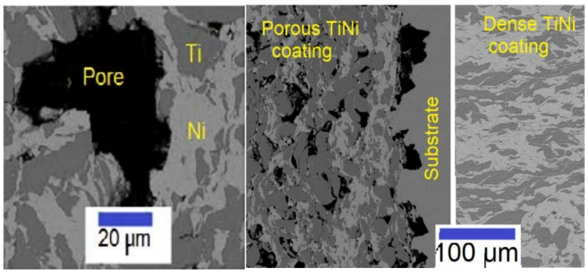


Figure 10- Variation of percentage (%) porosity and microhardness with standoff distance

Figure 11 shows the microstructure, morphology and pore distribution for TiNi coating fabricated by CS.



(a) (b) (c)

Figure 11- (a) Microstructure, (b) pore distribution and (c) dense TiNi coating

As shown in Figure 11(a), the phase for Ti and Ni are distributed as interlocked metal splats forming an excellently network. This microstructure accounts for the observed increase in microhardness values of the TiNi coatings compared to those of monolithic Ti and Ni powders reported in [32]. Figure 11(b) shows the morphology, shape and distribution of pores in the porous TiNi coatings. From this figure, it can be seen that the pore structure and location are of random nature, and the pore size ranges from few tens of micrometres to hundreds of micrometres which are favourable for bone in-growth, cell attachment and reduction of Young's modulus [2]. Figure 11(c) illustrates the dense TiNi coatings achieved under optimised spray conditions, compared to porous structures shown in Figure 11 (a) and (b). This demonstrates that CS can fabricate coatings with different percentage of porosity and microstructure when spray conditions are varied.

Finally, Figure 12 shows the stress/strain curve for cold sprayed TiNi powders. From this figure, it can be seen that the variation of stress with strain is widely spread due to perceive multiple slippage of shear plains between the Ti and Ni particles during tensile pull.

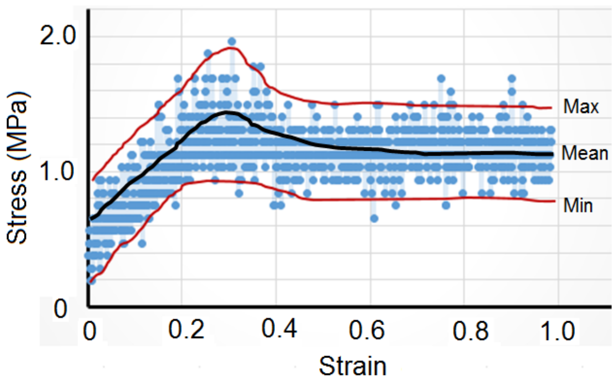


Figure 12- Stress/strain curve for cold sprayed TiNi powders

Based on the stress/strain curve shown in Figure 12, the deduced tensile strength and the Young's Modulus are 1.2 Mpa and 3 GPa, respectively. This Young's Modulus falls within the prescribed range of the bone implants. However, the tensile strength is slightly lower than the minimum recommended value [2], [3]. This suggests a weak inter-particle bonding which may be improved upon by heat-treatment of the cold sprayed TiNi coatings [2].

5 CONCLUSION AND FUTUREWORK

Ti and Ni powders with equiatomic ratio were successfully mixed using planetary ball mill. The resultant powder mixture was successfully deposited using CS process without partially melting and splashing away the TiNi particles. During CS, the central composite design of experiment proved to be a useful tool for calculation and selection of process parameters. This study demonstrated that CS can fabricate TiNi coatings with varying degree of porosity and microhardness. Further, the rapid deposition process and the inherent flexibility characterising the CS process makes it a promising process for competitive manufacturing of porous surfaces on TiNi bone implants. Further research will be carried out to establish the release of the Ni particles from the TiNi coatings and the influence of post spray heat treatment on the bio-mechanical properties of TiNi coatings.

6 ACKNOWLEDGEMENT

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8 BIOGRAPHY

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Professor Ionel Botef holds a PhD in Electrical and Information Engineering, a Masters in Mechanical and Manufacturing Engineering, and a degree in Pedagogy. He was previously involved for fifteen years in the aerospace industry with Rolls-Royce and Turbomecanica, has twenty-five years of academic experience, and is a registered professional engineer since 1993. The research interests include materials science, engineering systems, company integration, and interdisciplinary research. His research promotes the industrial application of advanced technologies. In this respect, he developed and commissioned the first laboratory in South Africa involved in cold spraying, an emerging and highly advanced technology with many possible aerospace applications.

A Cooperative Mobile Robot Network in ROS for Advanced Manufacturing Applications

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Abstract

Cooperative multiple robot networks have become a popular area of research in the past two decades due to the advantages of distributed networking systems as well as the potential benefits of robot teams working toward common goals. In advanced manufacturing environments, these benefits include the reduction of production bottleneck conditions during resource (robot) failures or the increased product throughput demands where robot services must be coordinated efficiently so that high levels of productivity are maintained. This paper discusses the utilisation of a software service, commonly known as the middleware layer, whose purpose is to mask robot heterogeneities, facilitate cooperation, and reduce robot configuration time due to the productivity constraints of most manufacturing plants. The focus of the paper is the control architecture design and application of a cooperative system of mobile robots using the ROS (Robot Operating System) middleware service.

Keywords

Robot cooperation, middleware, manufacturing.

1 INTRODUCTION

An increase in the use of technology in manufacturing industries over the past few decades has increased productivity margins for businesses and catapulted competition on a global scale. Manufacturers are always faced with the problem of maintaining high levels of product throughput while reducing operational costs. Productivity is the measure of the efficiency of production, which in turn is the ability to complete a job in the least amount of time and effort, while maintaining low levels of inventory and operational costs. In efforts to achieve high productivity, some manufacturers have seen the benefits of implementing lean manufacturing systems where production bottlenecks are mitigated amidst processing the correct amount of material at the right time by utilising resource management services [1].

Advanced manufacturing environments see the use of mobile robotics in their processes and the management of these resources (robots), in mitigating bottlenecks, are much more complex to deal with, since a network of robots can contain a great deal of heterogeneity [2]. The heterogeneities exist due to the varieties of sensors, actuators, and communication protocols, developed by different manufacturers, using different programming languages. An ideal cooperative robotic network would see the sharing of robot resources when there is a need (e.g. during bottleneck or scheduled maintenance events), however, an implementation of such an ideal would require the use of a software service, commonly known as the middleware layer.

One of the functions of the middleware layer is to reduce robot configuration time due to the productivity constraints of most manufacturing plants. The objective of this paper is to introduce the use of ROS as a middleware for cooperative robotics in manufacturing applications, and discuss a control architecture design of a system that has the potential to optimise manufacturing processes through robotic cooperation. The paper is outlined as follows: Section 2 discusses a literature survey on middleware platforms that can be used for cooperative applications; Section 3 covers a review on the ROS middleware architecture, with a focus on its communication protocol; Section 4 will see the design of a robot control architecture for manufacturing applications that will be integrated with the ROS middleware; while Section 5 discusses further research and concludes the paper.

2 ROBOT MIDDLEWARE

The middleware can be seen as the glue that links everything in the robotic network together; it should be designed in a manner that will allow for the easy integration of robots to the network, especially in applications where system configuration time is a critical factor. The middleware hides the heterogeneities in the robot network, provides a common platform, and reduces the software complexity for the programmer which, in essence, facilitates an efficient development process.

In any mobile robot application, where mission time is a critical factor, the middleware must provide the following functionalities:

- Automatic discovery and self-configuration: human configuration time of each robot in the network must be minimal, ideally non-existent.
- Secure, robust and reliable: the communication protocol must be secure and the system robust so that the quality of data is not compromised; this is critical to mission time and efficiency.
- Mask robot heterogeneity: provide a modular platform for software development and promote the optimal use of resources which also impacts the mission time and efficiency.
- Application interface: provide a simple platform for the development of user friendly application interfaces.
- Simulation component: a plug-in to the core middleware which facilitates the fast prototyping of solutions through iterative tests and simulation.

A robotic middleware used in distributed systems is the Internet Communications Engine (ICE) [3]. ICE is built using an object-orientated approach and is characterised for multi-platform and multi-language support [4]. The communication protocol uses ICE objects (an entity that resides in a local or remote robot), an interface, and clients. ICE objects reply to client requests by adhering to the behaviours that are defined by the interface. An application of the ICE middleware is seen in the development of the Multi-Robot Task Module (MRTM) – a software module developed with the objective of robots helping other robots by transparently including the behaviours performed by other robots into its own set of behaviours [4].

The ARCADE (Architecture for Real-time Control and Autonomous Distributed Execution) platform [5] uses the real-time database KogMo-RTDB [6] (originally developed for autonomous cars) as the central component in its framework. The function of the RTDB is to provide a real-time guarantee in the management and exchange of data objects, as well as the maintenance of data objects, during all local inter-process communication. The RTDB has shown that it is capable to handle large and complex sets of data while maintaining reliable real-time performance [7]. ARCADE accesses the RTDB by using interfaces, which are merely C++ classes with methods that operate on the data objects. ARCADE is also integrated with ICE to transfer data between RTDBs, thus information can be exchanged between robots in the network.

An example of a robotic middleware that provides self-configuration is the Physically Embedded Intelligent Systems (PEIS) Kernel [8] where all PEIS in the network are connected by a uniform communication model that permits the dynamic joining and leaving of the Kernel. The concept of the PEIS middleware is to use robot technology in smart environments and establish cooperation through many simple robotic components, rather than employing extremely advanced robots. A large number of PEIS experiments have been conducted, that utilise different robotic components accomplishing various tasks [9], [10].

The Miro middleware [11] is designed using an object-orientated approach and adheres to the Common Object Request Broker Architecture (CORBA) standard, which is a framework for developing and maintaining distributed software systems. Miro was applied in the research of heterogeneous mobile robot cooperation in search and rescue missions, where the capabilities of different robots were used to divide the search space by sharing sensor information and/or local maps [12]. The research also involved the development of pyMiro, a Python binding for Miro that enables the fast prototyping of Python-coded algorithms, eliminating the need for complex C++ code implementations.

The Player Project [13] is a robotic network server that provides a transparent interface for robot and sensor control. The server communicates with the robot hardware through device drivers and provides the client with standard interfaces to them, thereby masking the heterogeneities in the network. The simulation component of the Player Project is Stage, a two-dimensional simulator used to fast prototype development without the need for using actual robot hardware. Player has the availability of a large software library for device driver implementations.

The CoHoN middleware [14] was developed to operate with heterogeneous communication hardware and changes in the robot network topology, using a small message overhead which is crucial for communication efficiency and bandwidth. The middleware is structured on a topic-based publish/subscribe communication protocol and the message selection process is built through a multicast tree. In this process, the subscriber broadcasts the request, and if a particular node can respond with data it will return an answer; the subscriber then selects which node to receive the data from. The benefits of this communication method is the distributed approach to discover all possible data flow routes, as well as the avoidance of a centralised routing scheme.

A popular middleware platform used in the robotics community is the Robot Operating System (ROS) [15], which supports a client-server approach for control flow and publisher-subscriber method for data flow. The ROS middleware consists of nodes, messages, topics and services. Nodes communicate with each other in a peer-to-peer (P2P) manner by publishing messages and subscribing to published messages. The following Section discusses more about the ROS framework: the reasons for working with ROS, its basic communication protocol, and finally its limitations; this is necessary for the design and integration of the cooperation package into ROS.

3 ROS FRAMEWORK

ROS has become a middleware that has been widely spread in the robotics community, mainly due to the following reasons:

- Its free open source nature.
- The availability of a large software library for device driver implementations.
- ROS is a distributed system, so software nodes and user applications can run on different machines and they can communicate with each other.
- There are numerous commercial robots powered by ROS [16].
- ROS is beginning to be integrated into industry through the ROS industrial consortium [17], and is backed by well-known industrial players such as Yaskawa, ABB, BMW, and Siemens amongst others.
- ROS installs on the popular Linux Ubuntu distribution, and is actively developed and updated.
- Applications can be programmed in various programming languages.
- Due to its popularity, a great deal of help is available through wiki-tutorials, community forums and research papers.

It is by these reasons that ROS was chosen as the core middleware for the research discussed in this paper.

As discussed in the previous Section, communication in ROS occurs in a P2P manner, however, an initial event called the 'naming service' is centralised and relies on a master node, shown in Figure 1.

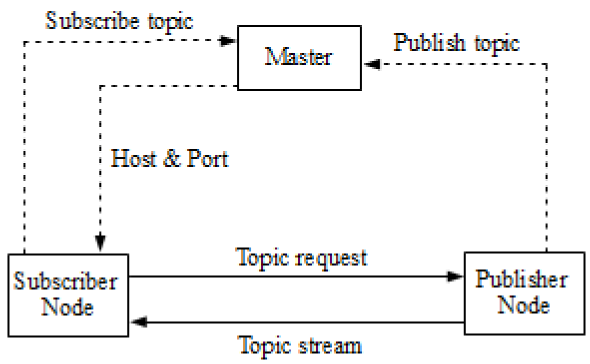

Figure 1 - Communication in ROS.

The communication sequence between a publisher and subscriber begins with 1) the publisher node registers the topic (e.g. a laser scan) to the master node, also referred to as the naming server, and informs the master about the entry point of topic data; 2) the subscriber node inquires the master on how to access the particular topic; 3) the master responds by sending the subscriber the entry point data, such as the host address and port number; 4) the subscriber now directly communicates with the publisher (host) via TCP or UDP connections, requesting specific topic data; 5) the publisher responds to the subscriber by sending the topic data stream (e.g. laser scan data).

ROS has been developed in a modular manner organised in packages, which can contain nodes, configuration files, libraries, datasets, or third-party software. The idea behind this form of software organisation is so that functionality of software packages can be easily integrated into the ROS framework. There is a wide variety of ROS packages available for various robotic implementations such as sensor/actuator drivers, robot path planning and navigation, robot simulation, and others [18].

The support of ROS for cooperative multi-robot systems is still limited, however, the contribution of the RCS (Robot Control System), discussed in the next Section, together with its future development and implementation, will expand the horizons of ROS in this area of research.

4 COOPERATION ARCHITECTURE DESIGN

In order to develop a control architecture design for the cooperation of robots in manufacturing environments, we need to identify the existing control system model used in most manufacturing plants and then modify the model to suite cooperative robotics. Design criteria must also be considered so that manufacturing processes are optimised and not hindered by the proposed cooperation model.

4.1 Control systems in manufacturing environments

Figure 2 gives a general hierarchical model of the control system approach taken by most process manufacturing operations.

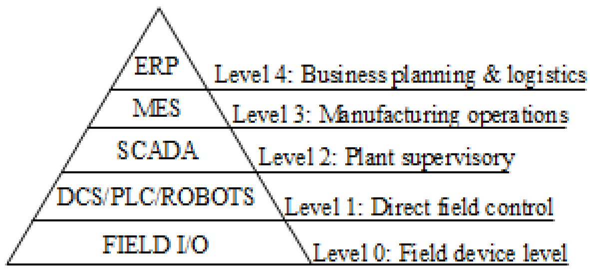

Figure 2 - Hierarchical control levels in manufacturing plants [19]

The level-structure in Figure 2 begins from the real-time response control and monitoring of field devices (e.g. sensors, actuators, digital signals) to the slow response, higher-level control of the manufacturing processes.

The DCS (Distributed Control System) and PLC (Programmable Logic Control) functions are geared toward the control of various mechanical, electrical, or process equipment. Robots also form part of this level due to the control of its own sensors and actuators through the use of its on-board microprocessor.

The purpose of the SCADA (Supervisory Control and Data Acquisition) system is to gather data from level 1 and present it in the form of graphics and trends for the operator or engineer to analyse and control on the plant floor. A level higher sees the MES (Manufacturing Execution System), whose function is to manage and schedule the engineering resources and processes so that productivity on the plant floor is optimised. The MES also bridges the gap between the manufacturing process and the business management level of the company.

Many companies utilise ERP (Enterprise Resource Planning) software packages that specialise in: 1) the planning of supply chains, production, and demand, and 2) the management of material, warehouse, maintenance and human resources. ERP systems add value to the business by assisting managers with meaningful information and tools to efficiently manage the various areas of the business.

4.2 Design criteria

Mobile robots in manufacturing environments usually work on one particular task to completion, however, in bottleneck scenarios cooperation may be required and robots should assist the task that will benefit the production process. The action resulting from a decision as to which task should be performed will not be autonomously executed by the robot for the following reasons:

- The Artificial Intelligence (AI) of the robot cooperation will be based on a machine learning system which is developing over time. The decisions made by the algorithm will not be accurate during the learning stage of the implementation.
- The human operator must be in ultimate control of robot resources due to his/her knowledge of robotic mechanical changes which may need to be maintained, thus limiting its ability to perform its primary task or cooperate.
- The human operator must have direct authority over the robot's decisions due to unexpected changes in production demand for particular products.

The above reasons mean that the AI system will be a recommender one; the operator will thus be able to choose whether or not to accept a particular task management decision made by the algorithm. In return, the algorithm will learn from the decisions made by the operator and over time, the AI should become an expert.

The following design criteria are also necessary:

- The ROS operating robots should be auto-discovered and self-configured by the robot control system, optimising configuration time.
- A simulation component will be included in the system, whose purpose is to fast-prototype solutions and aid in the development of further work in this area of research.

4.3 Robot control system design with ROS

The design of the control architecture for cooperative robots involves the inclusion of a Robot Control System (RCS) module in level 3 of the hierarchical model, as shown in Figure 3.

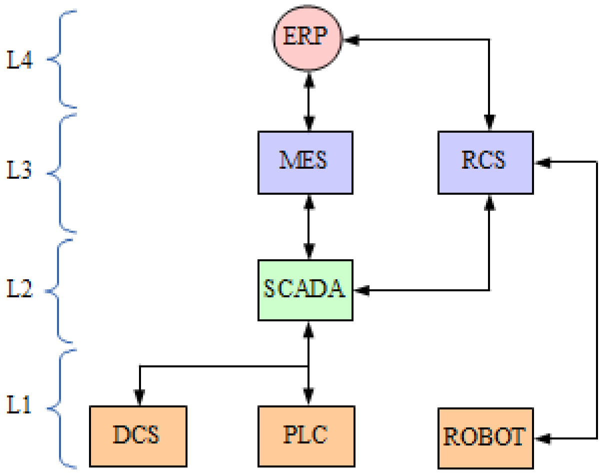

Figure 3 - Robot control system architecture for manufacturing

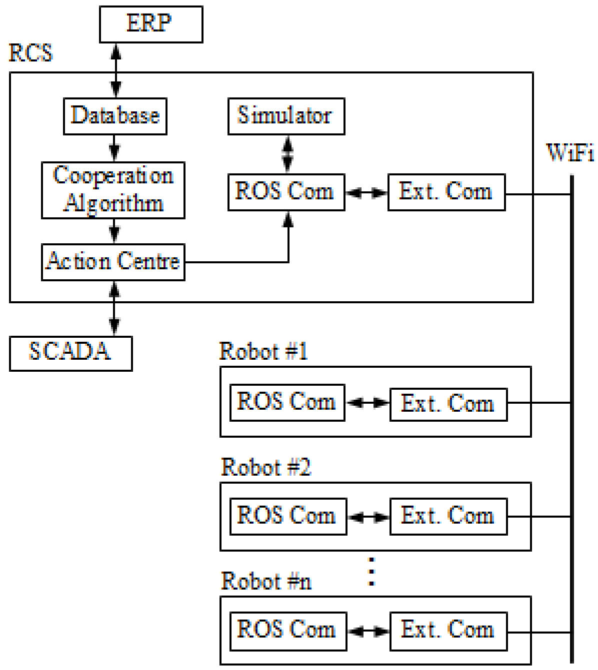

Figure 4 - RCS and ROS communication

The RCS communicates with: 1) the ERP to get historical and forecasted data for the learning algorithm, 2) the SCADA application for operator decisions on robot control, and 3) the robots in plant during initial configuration and at regular intervals during production. Figure 4 represents a more detailed composition of the elements involved in the communication between the RCS and each robot.

Each 'ROS Com' block in Figure 4 consists of a master and subscriber/publisher nodes as addressed by Figure 1. The reason behind using multiple masters in the multi-robot system is to increase the reliability of the system and eliminate the single point of failure. Also, individual masters mean that each robot has direct, real-time control over its sensors and actuators; this is a necessity in both single and multiple robot systems.

The 'Ext. Com' (i.e. external communication) blocks are necessary for communication protocol exchanges between the RCS and the robots. 'Ext. Com' is essentially a ROS package that will be developed to allow WiFi communication and the processing of data packets in the network.

There are many simulator packages that are available for ROS such as Stage, Gazebo, and pr2, however, none of them are specifically adapted for manufacturing applications. The design and development of the 'Simulator' block will see the use of ROS and simulated robot cooperation for manufacturing applications.

The RCS 'Cooperation Algorithm' is the brain of the system as it contains the learning algorithm used for the computation of the resultant recommended task goals for each robot. The learning data, obtained from different scenarios, are stored in the 'database' block.

Finally, the 'Action centre' block of the RCS decides whether or not to use the recommendation of the algorithm, based on the final decision made by the SCADA operator.

5 CONCLUSION AND FURTHER RESEARCH

The motivation for the research discussed in this paper stemmed from the need for optimising manufacturing operations by using cooperative robotics. The paper surveyed the various robotic middleware platforms that can be used for robot cooperation, one such platform among them being ROS. The communication methodology used in ROS was discussed and it was further described how ROS robots can be integrated into a cooperative manufacturing environment through the implementation of the RCS network. Further work in this research will involve the testing and simulation of the system through the use of a simulator package that is suitable for manufacturing applications.

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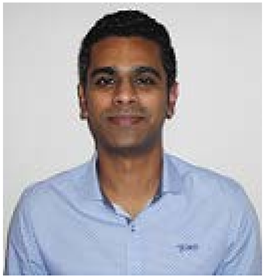

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A Hardware Supported Middleware and Autonomous Software Update System for Reconfiguration Management in the Reconfigurable Manufacturing Systems Paradigm

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Abstract
The further development of RMS technologies is highly important for future industries but there are many challenges in the implementation of a RMS, including complications during the system ramp-up after a physical reconfiguration. A RMS which was physically reconfigured has to have its control strategy reconfigured to match its new physical reconfiguration, currently this is handled manually, which slows the ramp-up time of the system significantly.This paper introduces a system which determines the physical state of the RMS and uses this physical state to reconfigure the control systems on the factory floor. The Reconfiguration Management and Middleware System (RMMS) uses indoor positioning techniques and a heuristic knowledge-based system intelligence to reconfigure the control on a factory floor rapidly and without human interaction. The system has accurately switched between control routines based on the physical state of the factory floor in under half an hour, as opposed to multiple hours of manual reconfiguration.

Keywords
Reconfigurable Manufacturing Systems, Autonomous Reconfiguration, Intelligent Systems, Indoor Positioning

1 INTRODUCTION

The modern manufacturing and industrial landscape has become dynamic and volatile and the requirement for manufacturing systems to respond rapidly to these changes has driven the development of Reconfigurable Manufacturing Systems (RMS) [1-4]. RMSs were first proposed by Koren et al [1] in 1999 and have been a major focus of research since. The RMS paradigm differs from Flexible Manufacturing Systems (FMSs) by having the ability to produce much higher part volumes while sacrificing some flexibility in part/product variety in the form of customisation. This production of only some subset of parts allows the cost to be lower per unit of production by minimising over-functionality. The RMS is aimed at Mass Customisation Manufacturing and other high variation batch manufacturing. RMSs aim to combine the high output of a Dedicated Manufacturing System (DMS) with some of the flexibility of a FMS. RMSs also aim to be able to integrate new or emerging technology with older machine tools and infrastructure, not requiring entirely new facilities to function. The ability of an RMS to scale itself to match market needs allows for cost-saving measures by allowing the RMS to be set up to match the demand, with not shortfall or excess functionality. RMSs benefit greatly from having a modular design – so that machine parts, tools, software or the machines themselves can be swapped out, changed or added to quickly and cost-effectively to aid reconfiguration.

A core aim of the RMS paradigm is the ability to rapidly and cost effectively swap between configurations in order to change product mixes or adapt to a new product production – that is, to be reconfigurable. This reconfigurability be achieved through 5 key characteristics, attributes, or aspects, outlined by Koren et al [1] and elaborated on in other papers [5-7]. These are; *Modularity*, *Convertibility*, *Customisation*, *Diagnosability*, and *Integrability*. The attribute of *Scalability* has since been added in multiple papers [3, 4, 8].

Middleware management is needed to facilitate communications between the high-level software systems (Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), and SCADA) and users (control and industrial engineers), and the heterogeneous machine controllers on the factory floor. This paper follows on from another paper by the same authors [9] and covers, in greater detail, some of the concepts put forward – but not described in detail – in that paper. Specifically this paper investigates the use of a Knowledge-Based System (KBS) to develop positional and configuration data obtained from the factory floor to assign new programs to the machines. The aim of this research was to speed up the ramp-up process of a RMS after a physical reconfiguration, by making the reconfiguration of machine and system control more streamlined.

2 BACKGRAOUND AND RESERCH GAPS

As discussed in section 1, the key aspects or reconfigurability need to be incorporated into a RMS from the outset of the system development in order to deal with market aims and challenges [1, 6]. These include; the need to produce variations, have a short delivery time, adapt to small volume orders, and maintain competitive costs and the challenges of market uncertainty and complexity of parts and part mixes [6]. Any system which aims to be incorporated into the RMS paradigm in the future must aim to address each of the key aspects and to enhance the RMS's key aspects.

A recent publication was presented by researchers from the Norwegian University of Science and Technology dealing with the development of a software framework for RMS [10]. The software, IceHMS, operates over an internet protocol and has many complex characteristics and produced a system which uses a relatively thin layer of middleware to communicate status information, controls and provide communication with a broad variety of machines (both type and brand) and aims to simplify the heterogeneity of a RMS. The layer researched in that paper was thinner than traditional middleware, it is still complex from a computer programming point of view and this research (indicated by the research title) included the creation of a very thin middleware layer with hardware support as an objective. This paper, along with others [11-13] shows that holonic concepts can make RMSs more practical and increase the reconfigurability of system control.

There were some gaps in current knowledge and implementation of RMS which this research has aimed to address, specifically relating to factory floor ramp-up after a reconfiguration and communication with heterogeneous entities. The manual reconfiguration of control is slow and requires further research and automation. The aim of this research was to increase the ramp-up speed of a RMS through the streamlining of the software reconfiguration process.

A previous paper on Middleware Managemnet [9] focussed on the problems faced when a RMS undergoes a physical reconfiguration. To summarise, after a physical change of the factory floor and switch between products being produced, the new, matching control strategy has to be applied to the machines of the factory floor. Currently, this is achieved by the manual upload of new control programs to each machine controller. This strategy is time- and labour-consuming and is prone to human errors. It was for this reason that this research has been undertaken. The previous research proposed the Reconfiguration Management and Middleware System (RMMS), which is explained in the following text, as a system which could make system ramp-up after a reconfiguration more rapid.

3 AN OVERVIEW OF THE RMMS

The RMMS has been described in high detail, at the system level, in the previous research [9], this section introduces the system-level design and operation of the RMMS. The RMMS operates using distributed modules, called State Communication and Software switching Modules (SCMs), attached to each machine controller and a central control computer, which runs the Central RMMS Control (CRC) software. The RMMS used these aspects to achieve the following:

1. The gathering of information (machine controller configuration and position) on the factory floor after reconfiguration;
2. Providing the decision-making software with this information;
3. Using and intelligent system to convert this information into a compatible set of machine software routines;
4. Passing software switching instructions from the central controller to the machine controllers via the SCM;
5. Feeding simple supervisory data from the machine controllers, via the SCM, wirelessly to the central control software.

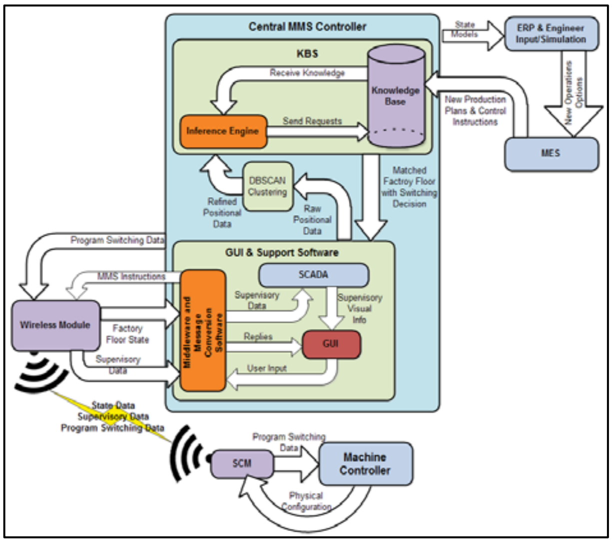

Figure 1 – System Structure of the RMMS

The RMMS uses the distributed SCMs as holonic agents which translate heterogeneous machine communication into one homogenous strategy which the RMMS operates with (and vice-versa). The modules are capable of wireless communication and position detection and wired communication with the attached machine controller. Using these capabilities, the SCMs are capable of communicating homogeneous information about the state of the attached machine. The CMC interprets the information from each SCM and uses it to build a model of the physical factory floor. Using Density-Based Spatial Clustering Applications with Noise clustering and a Knowledge-Based System (KBS), the RMMS is able to match the physical state of the factory floor with its required control strategy. The RMMS then wirelessly updates the control of each agent on the factory floor, thereby completing the reconfiguration process and improving system ramp-up time.

Figure 1 shows the structure of the RMMS and how data flows throughout the system – this figure should act as a reference point for the rest of the paper as each of the aspects of the system are explained in detail.

4 THE STATE COMMUNICATION AND SOFTWARE SWITCHING MODULE

The SCM is a piece of hardware which provides holonic modularity to the RMMS. It contains three fundamental duties – wireless communication with the central controller, wired communication with the attached machine, and position determination. The SCMs are made up of a microcontroller, a wireless communication module, a voltage regulation circuit, a logic-level converter circuit and a battery. The design of the SCM was discussed in detail in [9].

4.1 State Determination in the RMMS

The RMMS is capable of determining the physical state of a RMS factory floor through the combination of a RTLS and machine communication. Previois research has developed a plug-and-play controller which is aware of the physical configuration of the attached machine [14]. Using this controller an the RTLS, the SCMs are able to communicate the position and physical configuration of each machine on the factory floor, which is interpretted by the cantral middleware control software (CMC) and combined into a factory floor state.

5 THE REAL-TIME LOCATION SYSTEM

There has been much research into various real-time location systems (RTLSs), these pieces of modern research summarised in a dissertation by Mautz in 2012 [15] (a version this work was also published as a journal article [16]).

There are two options which were viable for use in the RMMS; a highly accurate option (±1cm) or a less accurate option (±1m) with an intelligent processing system. The more accurate options are more reliable but much more expensive and with a good processing system the less accurate option is reliable enough for the RMMS.

5.1 RTLS in the RMMS

The RTLS in the RMMS [9] uses a multilateration algorithm [17, 18] with Received Signal Strength Indication (RSSI) for distance estimation in order to estimate a machine's position on the factory floor. The RSSI is measured 20 times per beacon, because the measurements can be unreliable and good average is desired.

The Xbee Series 2 wireless modules which were used for wireless communication have a built in PWM RSSI pin. The microcontroller in the SCM is connected to this pin and uses the PWM signal to estimnate its distnace from each of 4 fixed modules on the factory floor. The multilateration locatisation technique then uses a form of triangulation to determin the machine's postion relative to the 4 fixed beacons. The following figure (Figure 2) shows the flowchart of the RTLS operation.

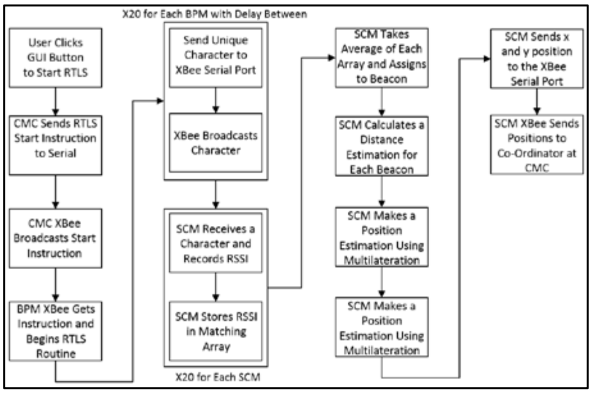

Figure 2 – Flowchart of RTLS Operation

The experiments conducted showed that the RTLS could locate a machine on a 12m x 10m populated factory floor to within a redius of 400mm ±85% of the time and to within a radius of 670mm in 100% of tested cases (the average error was 365mm).

6 INTELLIGENT PROCESSING AND PROGRAM ASSIGNMENT IN THE CMC

As discussed in section 5, the RTLS is a combination of multilateration localisation and some intelligent processing, the processing takes place once all position estimations have been recived from the SCMs. The CMC acts as the middleware and intelligence layer for the RMMS, it was designed as with a user interface and it refines and converts raw factory floor data into a usable factory floor model.
The processing works in two stages (shown in Figure 1), first the raw positional data is clustered into cells which make up a factory floor, then a knowledge-based system combines the clustered cellular layout with the configuration information for a physical model of the factory floor.

6.1 Clustering of Positional Data

There are many techniques for clustering data [19-21], but the density based algorithm, DBSCAN, was chosen for use in the RMMS. The DBSCAN algorithm has the advantage of being able to detect clusters which are not spherical in nature, which is of vital importance when clustering a factory floor model. The following experimental result shows how DBSCAN can cluster non-spherical groups and identify non-cellular units (noise). Noise could identify moving units such as materials handling bots or singleton cells. In the case shown below the minimum cluster size is 3.

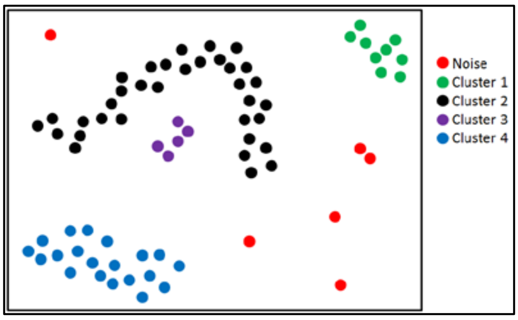

Figure 3 – DBSCAN Example Results

The algorithm had to be adapted for use in the RMMS, for this reason it was made fully object oriented, so that it used the x and y dimensional properties of a *Machine* object in the code (as defined by the data gathered by the SCMs) to gauge the distance between the machines and clustered the machines into a list of machines. At the end of the DBSCAN process, the lists were defined as *Cell* objects.

6.2 Program Matching using A Knowledge-Based System (KBS)

The KBS is a simple and well-proven form of artificial intelligence which is more simple to implement and more deterministic than some other methods of artificial intelligence. The system uses reasoning (an inference engine) and a base of known facts (the knowledge base) to solve a problem. When coded for a specific problem set the KBS can be simply set up and changed, making it very suitable for the task at hand, with the only real disadvantage being the large amount of data needed in the knowledge base in order to get meaningful results [22].

A KBS uses an inference engine and a base of known facts. In this system, the knowledge base is a database of *Layout* objects, each, in turn, made up of *Cell* and *Machine* objects. There are equivalence test methods built in to each of these three objects, named sameAs. The KBS's inference engine was designed to present the *Layout* as an argument to the sameAs method of the inference engine. The KBS was designed to draw a knowledge base from a locally stored file, in the form of a comma-separated value (CSV) file, which is created in MS Excel. The CRC contains code which retrieves values from the CSV file and converts them into layout objects. The KBS thus provides a method for the assignment of programs to machine controllers, based on factory floor state. The inference engine has the aim of finding a known factory floor state which matches the findings of the factory floor scan. The factory floor scan does not contain all the information necessary for the assignment of programs – the complete factory floor states are only known in the knowledge base. Thus, once a matching floor is found in the knowledge base the full details can be inferred to the incomplete state which was discovered by the first stage of the RMMS process. The known state found in the database, which matches the findings of the scan, contains all the software switching instructions necessary for the new programs to be assigned. Once the new assignments have been inferred, the RMMS sends the appropriate program assignment to each of the SCMs on the floor as discussed below.

In order to complete the process of reconfiguring the control of an RMS, messages had to be sent from the CRC to each module on the factory floor. The messages had to be configured to contain the SCM/Machine Controller's name and the program to which it had to switch. The switching of programs is the essential outcome of the system, it is process which updates the control at a factory floor level.
The process is handled by the CRC, when the KBS has found a matching factory floor state it places a pointer to its position in memory and essentially stores the matched, knowledge base state as the current form of the factory floor. The CRC then accesses the program assignment data stored in the matched state. Contained in the knowledge base is the program needed for each machine by the state. The CRC draws a machine name and its required program number and broadcasts it to the factory floor one-by-one. Each message is then received by each SCM, but only the one which is connected to the named machine reacts and sets its output to the appropriate binary combination. Once each message is sent out to the machine controllers, the process is complete and control is reconfigured for use in the new production period.

7 EXPERIMENTATION ON THE SYSTEM

Testing was done throughout the design process on each of the individual aspects of the RMMS and at the end of the research a complete system test was designed. The situation required a series of 4 hypothetical factory floor configurations (shown in Figure 4) to be set up in the UKZN Manufacturing and Mechatronics Laboratory. The RMMS's knowledge base was programed with 12 different possible factory floor states and was required to identify which state was present on the factory floor, match it to a state in the knowledge base, and send the program assignment instructions back to each SCM.

7.1 Aim

The experiment associated with the situation described above aimed to prove that it is possible, using the technology developed in this research, to rapidly provide software switching instructions to all the machines on a factory floor based on the physical state of that factory floor as identified by the SCMs.

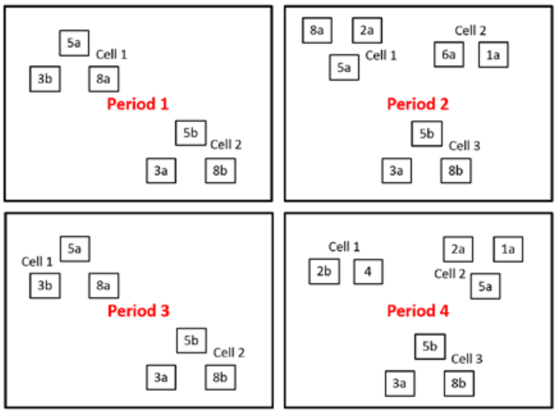

Figure 4 – Hypothetical Factory Floor Layouts

7.2 Method

In order to verify the success of the RMMS as a system the three reconfigurations (and the initial layout) needed to be physically laid out and the RMMS must have sent program switching instructions to each machine. The following method was followed:

1. Physically configure SCMs into Layout 1.
2. Use the Central RMMS Control software to initiate a factory floor scan.
3. Allow the CRC to build a factory floor state model.
4. Record the factory floor model as given by the CRC.
5. Use the CRC software to initiate a software reconfiguration.
6. Check and record the SCM outputs to confirm software switching.
7. Reconfigure the SCMs into the next Layout and repeat steps 2-6.

7.3 Results

As shown in Table 1, the system managed to successfully identify and reconfigure the control of each factory floor layout. The RMMS had an 80% success rate because the first time the system was run on Layout 2 a RTLS failure caused the system to fail early on.

Layout #	Run #	Identified Layout Correctly?	Assigned Programs Correctly?	Time	Result
1	1	Yes	Yes	16:17	Pass
2	1	No	N/A	05:32	Fail
2	2	Yes	Yes	20:22	Pass
3	1	Yes	Yes	17:04	Pass
4	1	Yes	Yes	19:55	Pass

Table 1 – Results of RMMS Test

7.4 Discussion & Conclusion

The experiment was successful in identifying the four states and providing software reconfiguration information to each SCM. Each process, from the initialisation of the program to when the assignment of program switching instructions took between 16min and 21min to complete. The process took longer for the layouts with more machines, primarily because the receipt of factory floor information from each module happens in a serial manner, as does the sending out of software switching instructions. This process is still very quick in industrial terms and is far more time and labour efficient than manual methods.

There weres some issues with communincation failure, but this was not an area of development. The process worked well and was successful in determineing the physical configuration and assigning a matching software configuration for every tested layout.

8 DISCUSSION

A core objective of the research and a requirement of the RMMS was the ability of the system to determine the physical configuration of the factory floor for the creation of a model. The creation of a model required a real-time location system, a refinement technique and a method for gathering the physical configuration of the machine.

The RTLS was able to locate machines on the experimental factory floor to within a radius of 600mm over 100% of the time. The addition of DBSCAN to the RTLS in order to refine results in a way useful in the RMS paradigm was an essential adaption which made a reasonably inaccurate but very cost-effective method for localisation feasible for the RMMS. The DBSCAN algorithm proved to be able to cluster the modules effectively with variations larger than those found in the RTLS experiments discussed above. The DBSCAN algorithm was able to correctly cluster simulated modules at an accuracy of around 90% when variations were limited to the extremes found in the RTLS tests (to within a radius of 600mm of the true position). The combination of the methods proved to be within the accuracy band which allows the KBS to make accurate software assignments for every one of the factory floor layouts tested in the system experimentation.

The hardware-supported middleware was the part of the research which had to handle heterogeneity in the factory floor controllers. This problem was originally dealt with using complex computer science techniques, but it was decided that a simpler, more universal, system would be needed for this research see [9].

9 CONCLUSIONS

In conclusion, this research helped to make reconfigurations of a RMS more economically viable and streamlined. This was obtained through the reduction of labour hours, human error, and ramp-up time. This streamlining was achieved through the development of the Reconfiguration Management and Middleware System. The RMMS was developed to handle the ramp-up of the system, through the rapid reconfiguration of software, thus speeding up the process. The RMMS developed in this research proved to be a desirable addition to the RMS paradigm, increasing the flexibility of a system in which it is implemented.

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Human-Robot Collaboration – New Applications in Industrial Robotics

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Abstract

This paper presents new possibilities for the application of human-robot collaboration (HRC). In addition to motivations for and benefits of HRC, a compilation of special robots is given. Furthermore, the upcoming technical specification ISO/TS 15066 is described, which sets force limits on contact forces for human-robot collaboration. Also, new applications for a robot-based assistance system for welding tasks, a work assistance system for assembly lines and a concept for force control of assembly processes for electrical cabinets are discussed.

Keywords

Human-Robot Collaboration, Assembly Technology, Human-Robot-Interaction

1 INTRODUCTION

Recent years have brought important changes to industrial robotics. Only a few years ago, working areas of humans and robots were strictly separated. Today, first industrial applications without protective means separating humans and robots have been implemented. A strong motivation for these developments is the use of specific human and robotic skills in combination. People contribute cognitive skills and can react very flexibly to new situations, while robots are tireless, can apply high forces and are very accurate. Furthermore, this approach allows the implementation of partially automated manufacturing solutions, which improve flexibility in face of small lot sizes and frequent equipment changeover.

The revision of the robot safety standard DIN EN ISO 10218-1 [1] and the publication of the robot system safety standard DIN EN ISO 10218-2 [2] enabled the use of automation solutions involving human-robot collaboration (HRC). A number of different robots have been developed to simplify the implementation of collaborative applications in industry. Well known examples are the KUKA iiwa [3], the robots of Universal Robots [4], the Fanuc CR-35iA [5], the Bosch APAS [6] and the ABB YuMi [7]. The new capabilities of the dual-arm robot ABB YuMi with 7 joints in each arm are also considered.

A major challenge is to design and set up a complete “safe” application. Current research activities are presented on the topic of human-robot collaboration. A multi-robot system is used to enable a welder to work effectively under optimal ergonomic conditions. Because of the heavy and bulky work pieces and the direct human-robot collaboration, robots with high payload are integrated into a safe application. For robotic assembly, customizable, robot-based assistant systems are designed. The possibilities include assisting employees or taking on tasks that cannot be performed by employees due to individual limitations. Additional research work looks at planning hybrid assembly lines, determining if a particular task in an assembly line shall be done by an employee, by a robot or if it should be implemented as a collaborative step. Rating criteria are for example cost, technical feasibility, implementation effort, required safety performance, ergonomics and availability. The virtual implementation and commissioning of hybrid and automated systems is also discussed.

2 MOTIVATION FOR HUMAN-ROBOT COLLABORATION

Human-robot collaboration is a possibility to combine the respective strengths of humans and robots in a joint task, for example industrial production. Humans with their cognitive capabilities are able to react to influences, such as defective components or changing parameters of parts and processes. Advantages of robots are the accuracy, repeatability, the handling of high loads and endurance.

The new topic of HRC offers many new possibilities. In some cases new applications are enabled, processes can be built up more efficiently by integrating robots into otherwise manual assembly systems or by using assistive robots for difficult tasks controlled by a worker. In other situations the investment in automation equipment can be focused on the most relevant manufacturing steps, maintaining a high degree of flexibility with respect to reconfiguration of the production equipment, while still introducing a partial degree of automation.

The various aspects above lead to the following requirements on HRC systems and their context:

- A quick and easy deployment, including dedicated functions and integration into overall production
- Increase productivity, decrease unit production cost, uphold quality for critical production steps
- Selective and scalable approach to automation, enabling flexibility with respect to changeover of production equipment and limiting investments
- Support and assist the employee in tedious or non-ergonomic tasks
- Intuitive human-robot-interface
- Clarification of the legal situation for suppliers, owners and operators of HRC systems

Nevertheless, those involved in manufacturing or using HRC systems can build upon initial market experience and on a developing standards portfolio.

3 STATE OF THE ART AND STANDARDS

3.1 State of the Art of Human-Robot Collaboration

In the past, physical contact between moving robots and workers has been totally forbidden. A contact was only allowed when the robot was deactivated. Today, one of the types of collaborative operation described in ISO/TS 15066 [8] (3.4) will allow contact events. Various research projects have dealt with the question of determining what sorts of contact events are acceptable. In [9], [10], [11] and [12] biomechanical phenomena and tolerance criteria are discussed. Specific investigations of models of human-robot collaboration are described in [13], [14], and [15]. In [16] the use of finite-element models (FEM) to analyse parts of the human body for their response to low-level mechanical impact is treated, resulting in a proposed classification scale.

An overview of the cooperation of human and machines in assembly lines is given in [17]. A safety assessment methodology for HRC with light-weight robots is described in [18]. In addition to the topic of safety, many research activities in the field of HRC deal with the communication between humans and robots, for example for the purpose of easily teaching or instructing collaborative robot systems (e.g. [19]).

3.2 Robots for Human-Robot Collaboration

To build up production systems with direct human robot collaboration, special robots with integrated safety features are needed. Such robots have become available over the past few years.

Nevertheless, robots suitable for collaborative applications are provided only with a “toolbox” of suitable safety features and safety functions. There may be default settings of these that serve to protect against the manipulator-related hazards alone.

The proper use of these functions in an application, however, is specific to the application and cannot be anticipated by the equipment supplier. Only the application-level risk assessment can determine which safety measures are required for the specific system.

In Table 1 we summarize the features of selected robot types intended for human-robot-collaboration.

Examples of other similar robots are Baxter and Sawyer (Rethink Robotics), Speedy-10 (Mabi Robotic), P-Rob 1R (F&P Robotics) and PF400 (Precise Automation).

Robot	Pay-load [kg]	Reach [mm]	No. of joints	Safety functions, monitoring: Joint Position/ Speed	Safety functions, monitoring: TCP Position/ Orientation/ Speed	Safety functions, monitoring: Other	Safety perfor-mance (ISO 13849-1)	Special features
KUKA LBR iiwa	7 / 14	800 / 820	7	Y / Y	Y / Y / Y	Y	PL d, cat. 3	Torque sensors
FANUC CR-35iA	35	1800	6	Y / Y	Y / Y / Y	Y	PL d, cat. 3	Dual force-torque sensors in base
Bosch APAS	4	911	6	Y / Y	Y / Y / Y	Y	PL d, cat. 3	Uses Fanuc LR-Mate 200iD
Universal Robots	3 / 5 / 10	500 / 850 / 1300	6	Y / Y	Y / Y / Y	Y	PL d, no cat.	
ABB IRB 14000 “YuMi” (Figure 1)	0.5	559	7 per arm	N / N	N / N / Y	N	PL b, cat. B	Inherently safe dual-arm

Table 1 - Selected robots intended for Human-Robot Collaboration

Figure 1 - Human-robot collaboration with the ABB YuMi (Source: ABB)

3.3 Relevant Standards

Whether one uses HRC or not, all machinery must follow the Machinery Directive (2006/42/EC) [20]. The Machinery Directive is converted into national law in all EU member states and provides a uniform European protection level for safety and health of industrial employees working with machinery. All machines that are produced in or imported into the EU are required to meet European technical and safety standards. The EC Declaration of Conformity for the machine and its CE-marking documents this conformity. Essential prerequisite for the CE-marking of a complete robot application is a risk assessment and the implementation of the necessary safety measures thus identified. How to do a risk assessment is described in EN ISO 13849-1 [21] and EN ISO 12100 [22].

The basic safety requirements on the robot and the robot system are described in the standards for the safety of the robot EN ISO 10218-1 [1], and for the safety of the robot system EN ISO 10218-2 [2]. They also specify four basic protective principles for HRC. These are “Safety-rated monitored stop”, “Hand guiding”, “Speed and separation monitoring” and “Power and force limiting”.

The application of these principles can be difficult without guidance more detailed than that given in the two parts of ISO 10218.

3.4 New Upcoming Standards Documents

As a result, the responsible ISO working group [23] has developed a so-called “Technical Specification” document, ISO/TS 15066 [8] to provide additional detail on the safety requirements on collaborative robots and applications. This guidance is aimed both at robot manufacturers and system integrators in their various roles and responsibilities in bringing forth an HRC application. In particular, the TS presents the safety requirements for each of the four basic types of collaborative operation. For each of these, we give a short summary of the relevant risks, the protective principle and comment possible implementation aspects. In all of the cases below, the protective principle applies in the shared, collaborative work space (CWS). It is noteworthy that practical applications will often be composed of a combination of more than one of the basic protective principles.

Safety-Rated Monitored Stop

The safety-rated monitored stop (SRMS) is the simplest form of HRC. In this collaboration strategy, the robot comes to a supervised standstill in the CWS, the space shared by worker and robot. During this standstill, the worker can enter the CWS and carry out his task, such as placing / removing parts into / from the end-effector. When this task is completed, the worker leaves the CWS and the robot can resume non-collaborative work automatically.

3.4.1 Hand Guiding

Collaboration according to hand guiding (HG) puts the worker into direct control of robot motion. The mitigation of the risks associated with robot motion is to effect robot motion only as a result of dedicated input from the operator. This input is given for example via a joystick or by means of direct input of external force onto a compliant robot, which then moves accordingly. Motion can also be constrained by programmed limits, such as “virtual walls”, fixed trajectories, and speed limits or similar, as the application risk assessment might require.

3.4.2 Speed and Separation Monitoring

Sharing a collaborative production task according to the speed and separation monitoring (SSM) protective principle allows for worker and robot to move in the same space. To mitigate the risks of contact, however, the robot must be controlled in such a way that the human cannot reach the robot while it is moving in a hazardous manner.

It is clear that this generates the need for safety-related detection of the worker in the collaborative work space by appropriate sensors. Furthermore, this information must be used by the robot controller so that the robot speed is adjusted to avoid moving contact with the worker. Online estimation of the stopping distance of the robot can be of advantage to recover the full productivity potential of this method.

3.4.3 Power and Force Limiting

Most eagerly awaited by the potential user community is the description of the power and force limiting (PFL) approach to HRC. According to this protective scheme, human and robot are working so closely that incidental contacts can occur. The mechanical and control design of the robot system, therefore, must render such contacts “harmless”.

The proper biomechanical limits for harmless contacts, both for sustained and for short contact, are provided in the TS for the first time. These limit values are based on pain sensation threshold research [12], a literature study on the estimated onset of minor superficial injury [9] and a simple model-based interpretation.

It is important to stress the need for an application level risk assessment to judge the risks associated not only with the robot manipulator, but also those introduced by the application (e.g. sharp edges on tools or parts). Depending on the outcome, it can be required to install additional safeguarding measures, beyond the proper configuration of the PFL protective scheme of the robot.

4 NEW APPLICATIONS IN INDUSTRIAL ROBOTICS

In this section, a selection of applications and manufacturing concepts with human-robot collaboration are presented. Application planning was done using FAMOS, a manufacturer-independent offline programming system [24]. To analyse the ergonomic conditions of the worker, a digital human model was integrated. It includes an evaluation of the body posture according to the Ovako Working posture Assessment System (OWAS) [25].

4.1 Robot-Based Assistance System for Welding Tasks

For the handling of heavy and bulky components in welding tasks, a multi-robot system with collaborative functionality assists the worker. Two robots position the components to be joined in the welding position, at which point the worker is able to carry out the welding task under favourable ergonomic conditions. In comparison to a standard welding bench, the worker need not assume awkward postures or work overhead, as all necessary positioning and orientation of the work pieces can be done by the robots. This also includes presenting the components in an optimal position for the welding process, allowing proper flow of the welding bead. Since the robotic repositioning motion is quite fast, the handling time, which presently is about one third of the total process time, can be reduced to a minimum.

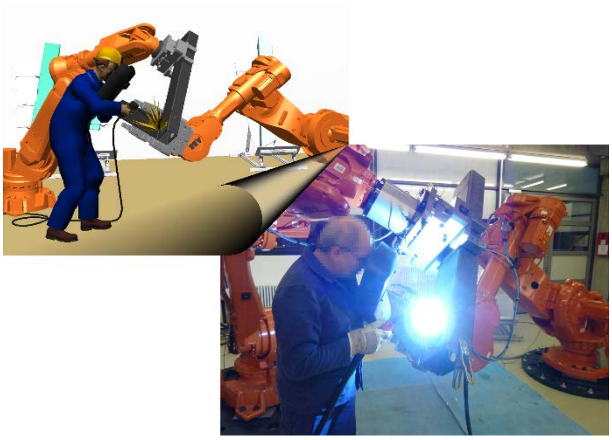

Figure 2 - Simulated and real HRC in a welding application

Integrated safety elements are a robot controller with safety-rated motion supervision, a safety-rated optical sensor system to monitor the collaborative workspace, and grippers with pressure control and pressure maintenance valve. The integration and the configuration use a combination of the collaboration principles SRMS and SSM. For example the robots can move their wrist axes only at reduced speed, the moving range of the main axes is limited to a minimum of a few degrees [26], [27].

4.2 Work Assistance in Assembly Lines

In another research task flexible, robot-based assistance systems are designed to assist workers with temporary or age-related physical limitations. Reference processes are repetitive tasks like tightening screws or even the handling of heavy and bulky parts. For these tasks, intuitive human-robot interfaces will be designed for the operator panel. The worker teaches the first three positions of the screws by hand guiding. The main technical element is the use of a KUKA iiwa with the integrated torque sensors and appropriate options. All remaining screw positions are computed, based on the assumption that all positions are in the same plane.

For a task in automotive final assembly, a robot can be installed instead of an inflexible handling device. The handling device is only force compensatory in vertical direction, while the horizontal directions must be moved by the worker. To reach the final position without a collision with the coated car body, an additional worker is needed temporarily to supervise the process. The robot, on the other hand, will assemble the component into the car body on a guided, pre-programmed, collision-free trajectory. Next to control tasks, the worker is able to do additional tasks, like guiding cables of the component [28].

4.3 Force Control in Assembly Processes for Electrical Cabinet

In the assembly of electrical components many processes are done in either fully automated or completely manual approaches. Especially in high cost countries, an increasing degree of automation is necessary to produce competitively. Often processes cannot be automated, for example when workers do optical or haptic quality checks in addition to assembly tasks.

As an example, we consider partially automating the installation and wiring of electrical cabinets for controls and automation systems. To focus on one of the typical steps, the analysis and verification of the force-distance curve for the insertion of an electrical contact bridge can provide a template for the control of the actual assembly task [29].

Recording and characterizing such a profile for a basic assembly task has two important advantages, both supporting the human worker in different ways.

Firstly, the principle profile of a contact insertion process will follow the profile shown in Figure 3, even if the length of the sections (1) and (3) along the distance axis and the height of the force threshold (2) may vary from one specific instance to another. Thus, preparing a template “assembly skill” according to the above profile provides a means for speeding up the programming of future tasks that can use this skill [30]. This approach can be taken with various other typical assembly motions, such as screwing, snap-fitting and others. The initial recording of the skill template as such can be achieved using compliant guiding of a suitable collaborative robot, while recording both distance and force together.

The second aspect that is addressed by this approach is that of quality control. While executing the above force-distance profile for a specific contact plugging task, the online recording of the actual force-distance characteristic can be compared to the stored ideal profile. Quality checking then constitutes verifying that the deviation between the two is below acceptable tolerances. Excessive deviations can be used to flag a quality problem.

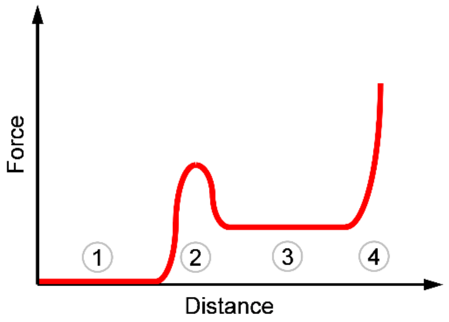

Figure 3 - Principle force-distance-diagram for the push process of an electrical contact bridge ((1) contactless robot movement, (2) overcoming the pre-tensioning of the electrical contacts, (3) sliding friction, (4) achieving full insertion)

5 REQUIREMENTS FOR A PLANNING SYSTEM FOR HRC IN ASSEMBLY TASKS

To simplify the planning of HRC systems in the future, the development of a planning system to support integrators or operators in the implementation process will be carried out. This objective addresses the following requirements:

- Easy and intuitive handling of planning tool
- Consideration of technical options including selection of robots and safety sensors
- Estimate of productivity, economic viability
- Consideration of constraints of the company (e.g. qualification of employees, company regulations), also with a view towards ergonomic work places
- Adherence to standards, guidelines and law, including safety requirements
- Consideration of components, tasks and processes

Work is ongoing to integrate the above aspects into a planning and support system for developing and implementing HRC applications.

6 CONCLUSIONS

The use of human-robot collaboration opens up new possibilities for additional flexibility in industrial production. The new document ISO/TS 15066 defines allowable force parameters for a contact between and humans and robots for the first time. A number of manufacturers now offer robots that enable the development of systems with direct collaboration of humans and robots. The aim of additional activities is to simplify the planning and implementation of HRC-systems by support tools.

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Design Life Cycle of a 3-D Printed Hydrocyclone

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Abstract

In mineral processing solid-fluid mixtures are separated in various ways. Of these, hydrocyclones are found to be a simple and low cost technique for particle separation. Additive Manufacturing (AM) technology has the potential to improve the design and testing process for hydrocyclones. The aim of this study is to evaluate the effectiveness of using AM and surface treatments to optimise hydrocyclone design. The hydrocyclone used in these experiments is based on a commercial model used in practice. The hydrocyclone was manufactured with a common plastic material (ABS$^+$) and was fabricated by use a Rapid Prototyping Additive Manufacturing (RPAM) technique. This paper describes the 3-D design printing (3DDP) and manufacture of a hydrocyclone design based on a commercial design using RPAM and a surface protection process. Based on the results of this study, this process has the potential to reduce development time and cost to produce an optimal hydrocyclone design iteration.

Keywords

Additive Manufacturing, 3-D printing, Particle separation

1 INTRODUCTION

In the beverage, chemical, pharmaceutical, water treatment and mining industries separation of particles suspended in liquids has always been a major task [1,2,3]. Many devices have been developed for this purpose. Included in this area are filters – both active and passive – screens and classifiers [4]. Among the group generally called classifiers, hydrocyclones have been developed as they are known to be simple mechanical devices with low costs (both in production, usage and maintenance) used specifically in particle separation driven by size and density differences. They have in the past been made of plastics, metals, ceramics and even glass.

A typical hydrocyclone is shown in Figure 1. Despite the above-mentioned advantages, there are still substantial challenges in the development of new hydrocyclones. The ability to design a specific hydrocyclone is limited due to the complexity related to the nature of the linkage between the hydrocyclone separation efficiency and its energy related performance.

Since the development of the first hydrocyclones (more than a hundred years ago), several researchers have worked on improving the efficiency of separation in the hydrocyclones. These researchers [2,5,6,7,8,9,10] have contributed – albeit it in a somewhat haphazard manner – both by improving or modifying the basic design. This has been most obvious in the investigation of parameters that affect the separation efficiency according to a variety of theories [2,7].

Due to the material cost and manufacturing time related to hydrocyclone design changes, research into the effect of geometric, physical, operating and dimensionless parameters on hydrocyclones performance and efficiency has been limited to scale model tests of the final designs. It is postulated that the separation efficiency could also be affected by the hydrocyclone manufacturing process. In fact, AM technology may have the potential to improve the design and testing process for hydrocyclones more radically than for other products.

In this also, surface engineering treatments can minimize wear and extend the component life. In addition, surface finish may be a critical parameter

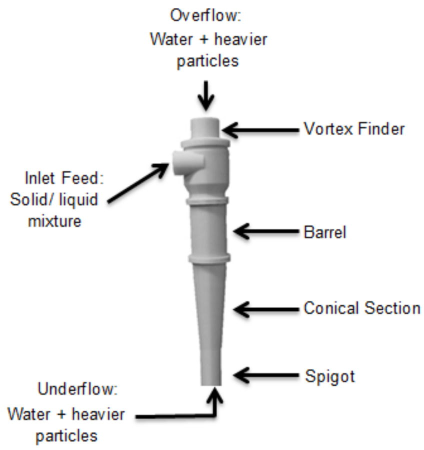


Figure 1 - 3-D Printed Typical Hydrocyclone

determining the practical performance life of the hydrocyclone. However, the effects of wear, especially on the inside wall of a hydrocyclone produced by AM has not yet been investigated. The aim of this paper is to evaluate the effectiveness of using AM and surface treatments to optimise hydrocyclone designs. The 3-D half scale hydrocyclone used in these experiments is based on a commercial model used in practice. The hydrocyclone was manufactured with a common plastic Acrylonitrile Butadiene Styrene (ABS^+) and was fabricated by use of a Rapid Prototyping Additive Manufacturing (RPAM) technique. Advantages of the RPAM are the rapid production, the relatively low cost and the ability to interactively address design changes in a short time. This paper describes the 3-D design and manufacture of an innovative hydrocyclone design based on a commercial design using RPAM and a surface protection process. This paper shows the analysis of the effect of using a 3-D printed hydrocyclone, for testing a hydrocyclone design, as opposed to the conventional design testing process for hydrocyclones with the aim to reduce development time and cost to produce an optimal hydrocyclone design iteration.

2 LITERATURE REVIEW

2.1 Design processes

Design processes have been studied for more than a century and have culminated in the classical work of Pugh [11]. Implicit in most such texts and research articles is that the design, evaluate paper design, prototype, evaluate prototype, make revisions process is expensive and of long duration.

Hague et al. [12] however, has the conception that integrating prototype production into the design phase itself started to be developed. They restricted their interest to impacts on the reduction of a complex assembly into a single complex object. This is in itself a radical notion for the period since they correctly understood that pre-AM era concepts around design from components upwards was now no longer a restriction.

2.2 Hydrocyclone design

Optimization is an advantageous method used to improve the design of a specific engineering device. The optimization of hydrocyclone design can lead to a decrease in the energy usage and maintenance in mineral processing industries. Many tools have been designed for the purpose of design optimisation. These tools consist of numerical simulation and experimental work. One of the tools used to simulate the flow within the hydrocyclone is computational fluid dynamics (CFD) [5,6,7,8,13,14,15].

Slack et al. [16], designed an automated process for CFD modelling of hydrocyclones. They have found that this method is not trivial. Even though CFD is time consuming (both computationally and physically) and expensive, many industries are still reliant on it to understand the complex fluid flow in hydrocyclones.

The most popular CFD models used to simulate the turbulent and multiphase flow (water-air-particles) in hydrocyclone are compared by Delgadillo et al [13]. They found that Large Eddy Simulations (LES) gives more accurate results than the Reynolds Stress (RSM) and renormalization Group (RNG) K-ε models. However, they did not validate the CFD results obtained. Hence, the design was not completely optimized. Another method called Lattice Boltzmann Method (LBM) used to simulate the flow in hydrocyclones was investigated by Bhamjee et al. [17]. They found that LBM could predict lower velocities than the Navier-Stokes model at a certain area; nevertheless, both models are in agreement. However, the low pressure values are not observed in the air core region. A review on hydrocyclone modelling for performance prediction can be found in [9].

Regarding these works an optimal hydrocyclone design cannot be fully optimised since the simulation results alone are not sufficient. They need to be validated using mathematical algorithms [18,19], or empirical formulae obtained via an experimental work [14,19]. The main factors that defined the optimal hydrocyclone design are performance (defined by the pressure drop) and separation efficiency [20]. For a (or many) given parameter(s) (geometrical or physical), the design is optimized on these two factors, tested and then validated. In general, the parameters are modified, simulated and tested. The cycle iterates until an optimal design is obtained. A schematic of the design optimization process is shown in Figure 2.

2.3 Rapid manufacture and design

The integration of design and prototype generation using a variety of RPAM techniques is well described in amongst others [12]. What is however not always clear is that the serious change to the whole design process that flows the ability to verify simple geometric questions, more complicated assembly issues and overall design issues by considering the printed design object.

Here we however, in Figure 2., wish to highlight the ability to further improve the design process's impact on the final design by the very tight integration of the physical object, the virtual object, the analysis using tools such as CFD and the rapid manufacture resulting in detail items.

It is in the confluence of advanced analytical tools (such as CFD) and rapid prototyping that the optimization of a product can proceed smoothly and in an organized and engineering sense.

2.4 Hydrocyclone performance

Generally, hydrocyclones performance and efficiency are studied from particle separation and fluid flow aspects. They can be affected by many variables: geometrical, physical and dimensionless, also by some variable related to the manufacturing process aspect.

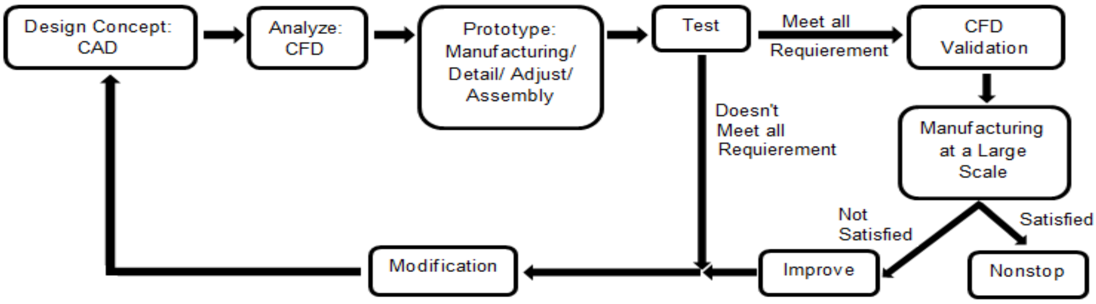


Figure 2 - Diagram of Design optimization of Hydrocyclones in Industries

Halls et al **[21]** have done an experimental study of particle separation using four cylindrical shaped micro-hydrocyclones (1 mm and 5 mm). These hydrocyclones were fabricated using micro-end milling and 3-D printing processes. The aim of her work was to compare the separation efficiency for both design processes used to fabricate the hydrocyclones. Unfortunately, the experimental works was only done for the 5 mm micro-milling hydrocyclone.

The study on the effect of surface roughness on the flow field of cyclone performance has been investigated by Kaya et al [22]. They have used experimental data and a mathematical model to validate the CFD simulations. They found that surface roughness due to corrosion and wear in the inner wall increases with a decrease of separation efficiency and performance of the cyclone. Unfortunately, this has not received much discussion for hydrocyclones. Since the surface roughness of a component depends on the material and/or manufacturing process used to fabricate it, then the material can have an effect on the total efficiency of separation.

3 DESIGN, ANALYSIS AND PROCESS

3.1 Why design changes and optimization

The normal procedure to design an engineering component requires a process not unlike Figure 2. However, from a realistic experience, the concept designs and assembly time is relatively shorter than the time to analyse the design. The design is optimized as described in section 2.2. But due to the complexity of the flow within the hydrocyclone, the turbulent and multiphase models used to simulate the flow require a large memory space.

Therefore, the physical (real world) time is also long. By also taking into account the failures, discrepancies and corrections in the design modelling, meshing, solution set-up and calculations, the time to analyse is even longer. We can believe that it is possible to reduce the total design time and cost by skipping the numerical analysis of the model.

In most industries, metal hydrocyclones are used for testing– even if they are then mass produced using other materials. They are made through traditional manufacturing techniques such as casting, moulding, machining, forming or milling [23]. However, this method presents many constraints: the material, machining and tooling equipment costs are high [24]. Thus, the production, testing and manufacturing time can be very costly and time-consuming. All these reasons encouraged us to come up with the alternative method to produce a novel hydrocyclone prototype with the available AM technology: 3-dimensional design printing (3DDP).

3.2 3D Design / Print and Manufacture processes

3DDP is an energy efficient, environmental friendly AM technique in which parts are made by adding layers of material layer-by-layer at a very small scale [25]. It finds its applications in industries such as food and beverages, aerospace, medical, fashion, architecture and sculptures [24]. Among the benefits this technology presents, the greater are that 3DDP is a tool-less process which decreases excessive material cost and printing time [24,26]. The advantage of printing a component piece by piece in detail is that, if a part is broken or doesn't meet the requirement, it can be reprinted without the whole component being modified. 3DDP can be

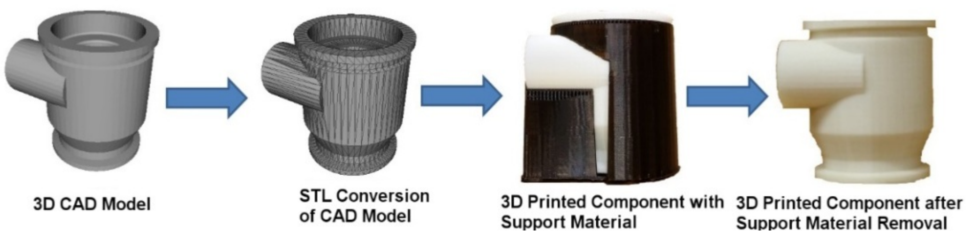


Figure 3 - 3-D printing process: From CAD model (left) to printed component (right)

used by individuals at home or by big companies and 90% of the material is used during the process [23,26].

The process used to print the ABS+ hydrocyclone was Fused Deposition Modelling (FDM) [23,24]. It consists of extruding and heating the thermoplastic (ABS+) and any support material through a heated extruder layer-by-layer onto a build platform. A schematic of the 3DDP process for the hydrocyclone is given in Figure 3.

The results obtained, in terms of development time, testing time and cost, will be compared with those of the conventional metal hydrocyclone.

4 EXPERIMENTAL SET-UP

In the set-up represented in Figure 4, for each test the sump was initially filled with water and all valves were opened except the hydrocyclone inlet line. The pump was primed and switched on and all the liquid was allowed to flow from the sump to the bypass line. This was done in the purpose of releasing the high pressure and eliminating the air bubbles in the water.

concentration. However, the errors in the results can come from the slurry pump, which had to be run and cooled down every time before proceeding with a

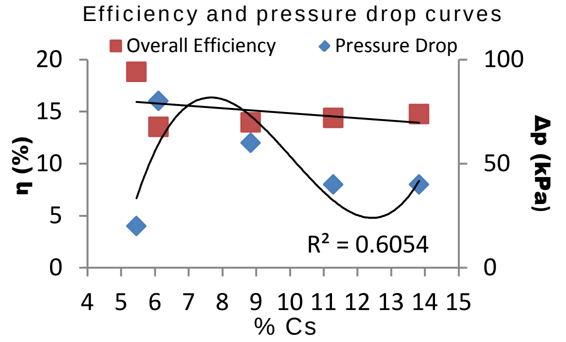
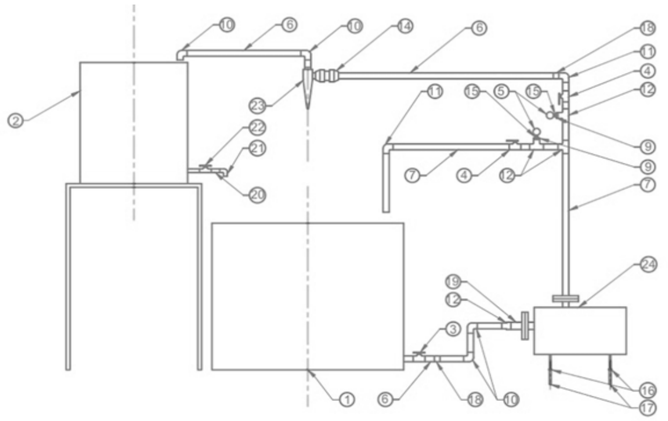


Figure 5 – Efficiency and Pressure Drop versus Solids Feed Concentration

variation in the testing parameters. Also the particles need to be continuously stirred to avoid silicate crystallising quickly and settling at the bottom of the sump. Although the different challenges encountered during the testing, the 3DDP hydrocyclone presents many benefits that will be shortly discussed in the next sections.



24	1 OFF	PUMP
23	1 OFF	HYDRO CLYCLONE
22	1 OFF	Ø 25 PVC BALL VALVE
21	1 OFF	Ø 25 90deg BEND
20	100mm	Ø 25 PVC PIPE
19	150mm	Ø 50 STEEL PIPE
18	2 OFF	Ø 40 MALE-FEMALE
17	4 OFF	M10 CHEMICAL ANCHORS
16	4 OFF	VIBRATION DAMPENERS
15	2 OFF	Ø 8 NIPPLE
14	1 OFF	Ø 40 PVC CONNECTION
13	1 OFF	Ø 40 NIPPLE STEEL - PVC
12	1 OFF	Ø 50 - 40 REDUCER PVC
11	2 OFF	Ø 40 90deg BEND STEEL
10	4 OFF	Ø 40 90deg BEND PVC
9	2 OFF	Ø 40 - 8 REDUCER
8	3 OFF	Ø 40 STEEL T BEND
7	2650mm	Ø 40 STEEL PIPE
6	3500mm	Ø 40 PVC PIPE
5	2 OFF	PRESSURE GAUGE
4	2 OFF	Ø 40 BALL VALVE
3	1 OFF	Ø 40 GATE VALVE
2	1 OFF	Ø 700 TANK
1	1 OFF	Ø 1250 TANK

Figure 4 - Diagram of the experimental set-up [28]

Thereafter, silicate powder of density 2650 kg/m^3 was introduced into the sump, and agitated via the bypass system. During the experimental runs, the inlet, underflow and overflow flow rates were collected and measured for a certain time using the gravimetric method.

5 RESULTS

The design related results obtained from the testing are presented in Figure 5. The effect of particulate feed concentration on the pressure drop and the separation efficiency is seen in Figure 5.

In Figure 5, it can be seen that there is a non-linear relationship that makes direct analysis and simulation unlikely to determine the exact optimum design point. As demonstrated the expected pressure drop decreases with an increase of solids

feed concentration. It is also important to note that the efficiency varies nonlinearly with the solids

5.1 Design benefits

From the nature of classical design from Pugh [11] it is clear that the process after the freezing of specifications is to some extent linear and allows only for revisiting previous steps in the case that specific design errors occur. In the present era however we must move beyond design changes required by errors to a more pro-active process where the changes during the final design phase and the physical testing phase merges into a more active design/test/revisit process that uses the nature of modern 3D printing and rapid manufacture to ensure, as shown in Figure 2, that design optimization becomes the norm rather than the exception. In the case where, as in hydrocyclones, there is still the need to use analytical tools that require calibration (such as CFD) the time involved in the design phase can be extended dramatically if optimal design is only achievable by repeated analyses with varying parameters. Then calibrating the analytical results at one or two parameter points using physical model testing allows a much more directed change in design parameters to enable optimal designs to be achieved. In Table 1, we attempted to illustrate a comparison of the time, cost and design benefits of the 3DDP and the other traditional manufacturing processes (milling, casting, etc.) use to manufature the metal hydrocyclones.

5.2 Time benefits

Often prototype development times are a serious constraint in the use of such devices in the design cycle. The prototype requires a more manual approach since the tooling and setups for production cannot be made for a single item. It is in this case that 3DDP is excellently suited to the problem of prototype development and testing in the design loop.

The total time for production of a suitable hydrocyclone was checked with two developers of such devices in the minerals beneficiation industry. The time from final design approval of the hydrocyclone to it being ready for testing varied from 12 to 26 weeks in general. The time involved in producing the prototype using the 3DDP process was slightly less than 2 weeks. This allowed a much more rapid transition to the testing phase and repeated testing of variants.

5.3 Cost benefits

Often prototype costs are a serious consideration in the use of multiple prototypes to test design changes since the costs of such handmade prototypes is typically substantially higher than for a production run version of a completed design.

Costs for a prototype of the hydrocyclone were checked with a physical producer of such devices and anecdotally it appears that the cost of a single prototype hydrocyclone for testing purposes could range from R15, 000 to R150, 000 for up to five design iterations [27]. The above cost is based on changing only one aspect of the hydrocyclone for example the cone design. The above data is based on a 100 mm diameter hydrocyclone and would be substantionally higher for larger hydrocyclones [27]. The full cost of a single iteration of the printed hydrocyclone was only R6, 000.

6 DISCUSSION

The final results of the design and testing can be summarized as follows:

1. Design using an integration of simulation, design and rapid prototype testing has shown an improvement in the hydrocyclone performance. Actual optimization can be achieved in minimal time and cost for complex systems that need some form of physical calibration.
2. Separation efficiency can be positively affected by the process in 1. Above beyond the levels that simulation using only CFD would allow.
3. 3DPP as a process allows substantial cost savings in a design situation where a large number of variables are involved in a nonlinear manner and the interaction of these variables is difficult to predict even using advanced simulations.

These results are summarised in Table 1.

	Design Testing Period	Cost
3DDP hydrocyclone	Less than 2 weeks	R6, 000
Fabricated metal hydrocyclone	12 to 26 weeks	R15, 000 to R 150, 000

Table 1 - 3DDP compared to fabricated metal hydrocyclone testing process

7 CONCLUSIONS

The design and optimisation process proposed in this study has the potential to reduce development time and cost to produce an optimal hydrocyclone design iteration. The substantial cost and time savings, in the optimisation of a design, made using the process of leveraging 3DDP to produce and test several design iterations, provides a designer with an effective means of exploring a design situation where a large number of variables are involved in a nonlinear manner and where the interaction of these variables is difficult to predict even using advanced simulation software, such as in the case of hydrocyclones.

The nature of classical design relegates the process of benchmarking a design to the end of the design process, almost leaving it as an afterthought to the paper design. By ensuring a tighter integration between the design and testing process as well as analysis of the design, via the leveraging of 3DDP and analysis as in this study, design optimization may become the norm rather than the exception.

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9 BIOGRAPHY

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Solution Heat Treatment of Single Crystal Castings of CMSX-4 Nickel-base Superalloy

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Abstract

An investigation of the microstructure and mechanical properties for heat treated directionally cast rods, produced from the nickel-based superalloy, CMSX-4, is presented. The rods were cast using the Bridgman method for manufacturing single crystal structures. The microstructure of the cast rods consists of γ and γ' precipitates. This microsegregation has a negative effect on the microstructure and, hence, the mechanical properties of the castings. The solution heat treatment of the second generation, single crystal Ni-base superalloy, CMSX-4, is known to dissolve the eutectic γ and γ' region. This requires temperatures up to 1316°C and approximately 45 hours total time. These high temperatures and long processing times result in high costs. The aim of this study is to investigate the effect of the heat treatment protocol on the extent of improvement of quality of single crystal castings, as a basis for determining cost feasibility in practice.

Keywords

Nickel-base superalloys, CMSX-4, single crystal castings, solution heat treatment.

1 INTRODUCTION

During solidification through the mushy zone of the Nickel base superalloy, CMSX-4, some of the solute elements prefer to remain in the liquid phase while some elements preferentially diffuse to the solid phase forming a chemical heterogeneity in the solidified structure with a significant fraction of γ and γ' eutectic at the interdendritic region. It has been established that Co, Cr, W, Mo, and Re segregate preferentially to the dendrite cores, while Ti, Al, and Ta segregate preferentially to the interdendritic region. There are two important effects of this microsegregation in the solidified structure: chemical heterogeneity and microstructural heterogeneity. These effects have a direct impact on the mechanical properties and hence the performance of superalloys as high temperature materials.

The γ' precipitates in the interdendritic region of a solidified structure are coarse, irregular shaped and incoherent. Since the γ and γ' interface plays a major role in the development of strength and creep resistance, it is always desirable to have fine, uniform and coherent cuboidal shaped precipitates throughout the microstructure. The chemical heterogeneity in the solidified structure leads to chemical instabilities. Dendrite cores in the solidified structure, being rich in Cr and Re, are preferred locations for formation of the embrittling TCP phases that degrade both the creep and fatigue resistance of the alloy [1-3].

Solution heat treatment is a lengthy process; moreover it is also quite energy and capital intensive, and hence expensive. For this reason, a multistep cycle heat treatment process has been developed for single crystal castings, designed to completely solution the γ' and the most of the γ and γ' eutectic without incipient melting. Heat treatment is also used to reduce residual stresses in castings resulting from the casting process [3].

The all-important mechanical properties for turbine blades, as an example, (such as high-temperature creep resistance) depend largely on the alloy composition, given in Table 1, and on a proper heat treatment protocol. Microsegregation after casting can have either a beneficial or a deleterious effect on the property of the cast product. Most significantly, the chemical inhomogeneity associated with microsegregation usually leads to poor corrosion resistance. For these reasons, nickel-base superalloy turbine blades are subjected to a homogenisation heat treatment, so as to reduce or eliminate residual segregation patterns, and in order to re-dissolve non-equilibrium secondary phases produced by microsegregation [7-8].

Traditionally, two heat treatment stages are used for nickel-base superalloys. First is the solution heat treatment, designed to homogenise the microstructure and reduce the effects of segregation. Second is one or multi-step aging, designed to develop cuboidal γ′ precipitates.

This research focuses on the effects of solution heat treatment on directionally cast nickel-base CMSX-4 superalloy castings, through metallographic and mechanical property investigations [1-3].

2 MATERIALS AND EXPERIMENTAL PROCEDURE

Single crystal (SC) castings from the second generation Ni-base superalloy were produced in a VIMIC 2 E – DS/SX vacuum investment casting system manufactured by ALD Vacuum Technologies. The single crystal samples were cast in the [001] direction at average temperature gradient of 1.5 K/mm and withdrawal velocity of 3 mm/min (Bridgman Process for directional solidification). The chemical composition of the alloy is shown in Table 1.

Elements	Cr	Co	Mo	W	Ta
Weight %	6.5	9.0	0.6	6.0	6.5
Elements	Re	Al	Ti	Hf	Ni
Weight %	3.0	5.6	1.0	0.1	balance

Table 1 - Nominal compositions of CMSX-4

The heat treatment of the castings was performed in a laboratory vacuum furnace equipped with an induction heating system of 80kW total power, a working chamber of 600mm x 400 mm x 400mm, and a set of 9 sleeve protected thermocouples with a temperature measurement accuracy of 3°C. The heating process can be performed by convection to 950°C (in argon or helium atmosphere) or radiation to 1350°C (in vacuum). The furnace is equipped with a vacuum system consisting of a rotary and diffusion pumps capable of generating a vacuum of $5 \cdot 10^{-5}$ bar.

It is well known that single crystal alloys cannot be used for the intended high temperature applications through solution heat treatment only. Since the solidus of polycrystalline alloys is below the γ' solvus temperature, this prevents the complete dissolution of γ' using solution heat treatment. The increased melting temperature of single crystal alloys frequently allows refinement of the γ' microstructure with a solution annealing followed by two aging steps. In the cast alloy with a high volume fraction of γ and γ' eutectic, the complete dissolution of γ' by the appropriate heat treatment is of extreme importance. In addition to dissolving the γ and γ' eutectic and solutioning the γ' for subsequent re-precipitation, the solution heat treatment also reduces the chemical segregation of the elements.

Heat Treatment Stage	Temperature-time settings
Solution heat treatment (annealing)	1277°C / 4h → 1287°C / 2h → 1296°C / 3h → 1304°C / 3h → 1313°C / 2h → 1316°C / 5h → GFC*
Aging 1	1140°C / 6h → AC**
Aging 2	871°C / 20h → AC**

* Gas furnace quench ** Air cooled

Table 2 - Heat treatment protocol

The experimental observation of solution heat-treated samples were obtained through metallographic examination and analysed using both Scanning Electron Microscopy (SEM) and Optical Microscopy (OP) at all stages of the heat treatment process. These stages were chosen as follows:

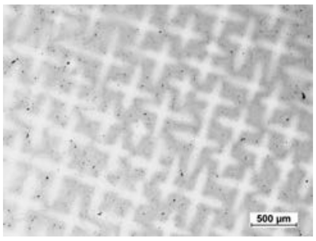
1. Samples after solution heat treatment;
2. Samples after aging 1;
3. Samples after aging 2.

For determining the crystal orientation, the Laue method was used, while hardness tests were undertaken to determine the mechanical strength of the samples.

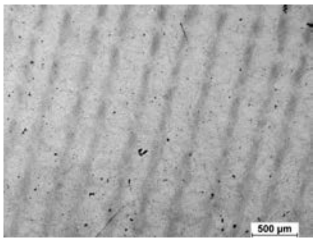
3 RESULTS AND DISCUSSION

3.1 Investigation of microstructure using OP

Figure 1 presents optical photomicrographs of the interdendritic region of solution heat treated CMSX-4 samples showing single crystal microstructure of the castings after different heat treatment stages. It can be seen that the γ and γ' eutectic has been dissolved.



(a)



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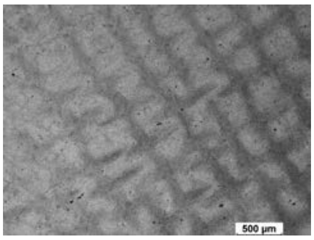


(c)

Figure 1 - Microstructure of heat treated sample after the following stages: (a) solution heat treatment (annealing), (b) aging 1, and (c) aging 2

3.2 Investigation of microstructure using SEM

For the SEM investigation, a 10% H_3PO_4 solution etchant was used. This etchant was prepared for electrolytic etching with the following parameters:

voltage 3 Volts, amperage 0.2 Amps, time duration 3-5 seconds.

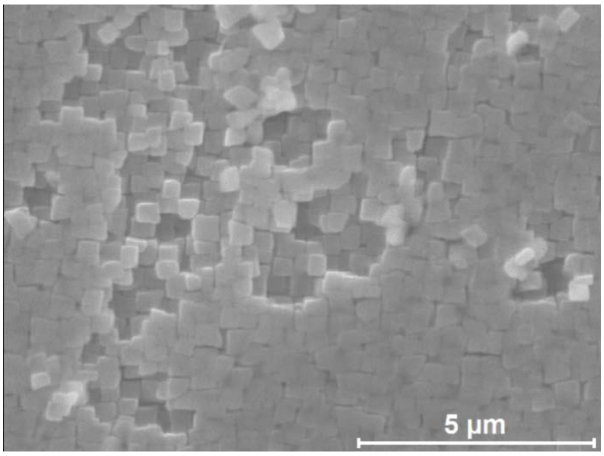


Figure 2 - Sample after annealing.

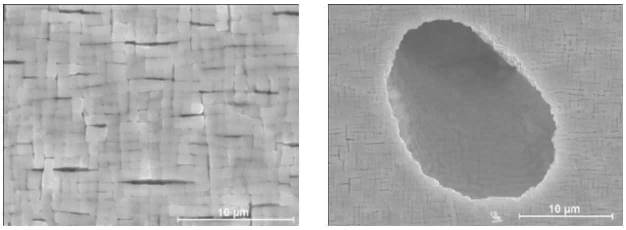


Figure 3 - Sample after aging 1, with evidence of gas porosity (right).

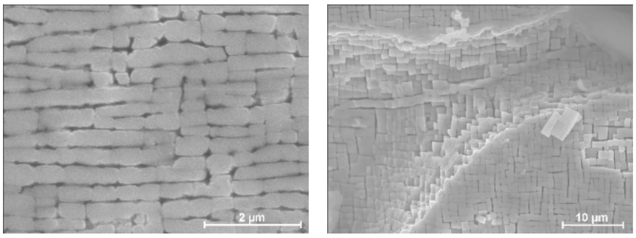


Figure 4 - Sample after aging 2 - dendrite core.

The microstructure of the heat treated samples following each step of the heat treatment indicates that the γ' and the γ/γ' eutectic completely soluted after the end of the solution heat treatment (annealing) stage.

3.3 Mechanical Properties: Hardness

Mechanical hardness tests were performed for the single crystal castings after each of the three different heat treatment stages, in addition to the as-cast samples. The results obtained show an improvement in the mechanical hardness property of the Nickel-base superalloy after the heat treatment process.

Test Sample	Hv (kg/mm^2)
As-Cast sample	436
Solution heat treatment	483
Aging 1	438
Aging 2	472

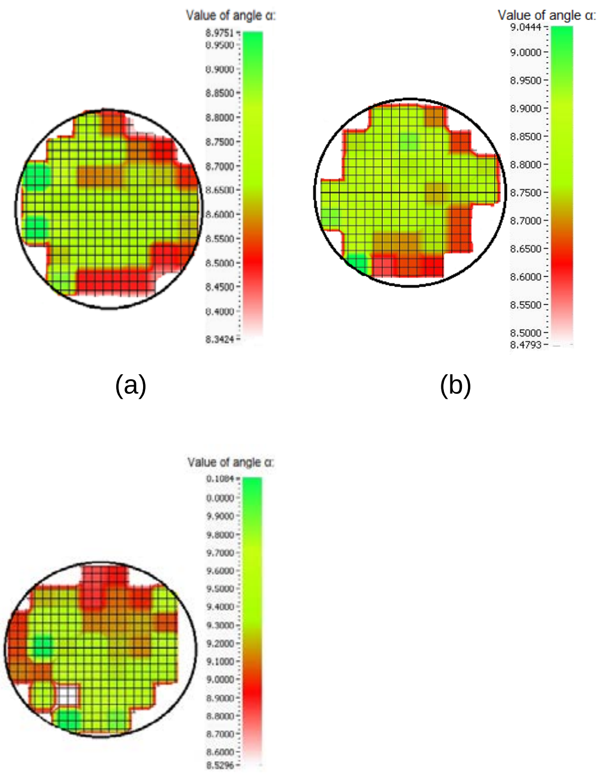
Table 3 - Vickers Hardness Hv

3.4 Diffraction Analysis for Single Crystal structures after heat treatment

A specialised X-ray EFG diffractometer, equipped with a goniometer allowing evaluation on three-dimensional surfaces, was used to determine the crystal orientation distribution on the surface of the single crystal castings. Only samples without defects (such as slivers, freckles, low angle boundaries or high angle boundaries) were used in this investigation. The crystallographic orientation of the samples was determined by Laue back-reflection techniques.

The strength of metals decreases with increasing temperature. Since mobility of atoms increases rapidly with temperature, it can be appreciated that diffusion–controlled processes can have a very significant effect on high-temperature mechanical properties. The assessment of crystalline quality, including the crystallographic orientation, is a very important element of manufacture of single crystal castings made of superalloys.

Superalloy castings display anisotropic mechanical behaviour, in which the material properties (and hence mechanical properties) depend on the crystallographic direction. Hence, the assessment of the crystallographic orientation of single crystal castings forms the basis for determining the mechanical properties of the castings.



(a) (b)

(c)

Figure 3 - Crystallographic maps indicating the angle of deviation α at the base (a), in the middle (b) and at the top (c) of the single crystal as-cast samples.

For acceptable mechanical performance of the castings, it is generally required that the value of the angle of deviation α from the [001] direction (the single crystal growth axis) should not exceed 15°. The greater this angle of deviation, the lower the creep resistance of the castings.

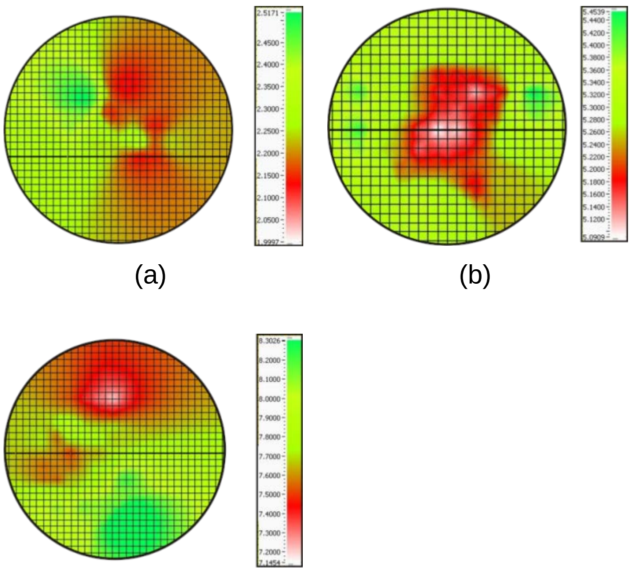
Firstly, the cross-sections of the as-cast castings were investigated at three points along the blade axis.

The map (distribution) of the crystallographic orientation on the studied surfaces is given in Figure 5. The angles of deviation α between are found to range between 8.75° and 9.40° as shown in Table 4. This proves a relatively high degree of structural homogeneity.

As Cast Sample	Angle of deviation α ± 1.0
1 (base)	8.75
2 (middle)	8.80
3 (top)	9.40

Table 4 - Values of deviation angle α from the single-crystal growth axis for the as-cast samples.

Secondly, the cross-sections of the heat treated samples were investigated at the same surfaces as for the as-cast samples. These resulting crystallographic maps are shown in Figure 6.



(a) (b) (c)

Figure 6 - Crystallographic maps indicating the angle of deviation α for the (a) solution heat treated sample, (b) after aging 1, and (c) after aging 2.

The maps (distribution) of the crystallographic orientation on the studied surfaces are given in Table 5.

Heat Treated Sample	Angle of deviation α±1.0
1 – Solution heat treated	2.20
2 – aging 1	5.09
3 – aging 2	7.70

Table 5 - Values of angle α describing the deviation of the [001] γ' direction from the single-crystal growth axis for the heat treated samples

All values of the angle α are smaller than 15^0 and comply with global manufacturing standards in the aircraft industry. The lowest value of the angle α is found to occur after the solution heat treatment process, which indicates that the heat treated castings will have the highest creep resistance, a critical requirement for turbine blades which operate under high temperature conditions.

4 CONCLUSIONS

The solution heat treatment of the nickel-base superalloy, CMSX-4, results in the elimination or reduction of microsegregation. This allows the manufacture of castings of a more uniform, homogeneous microstructure.

The evaluation of the microstructure using both OP and SEM shows transformation of the dendritic structure to cuboidal γ/γ′ microstructure.

The solution heat treatment (annealing) process dissolves the γ/γ′ eutectic regions early in the heat treatment cycle at temperatures up to about 1316°C.

The mechanical properties investigation by hardness measurement has shown improved properties for the solution heat treated samples as compared to the as-cast samples.

This research has successfully shown that the solution heat treatment process dissolves both the γ′ precipitates formed during cooling from solidification and the γ/γ′ eutectic, and reduces the degree of chemical segregation due to the partitioning of some of the elements to the dendrite core and interdendritic regions. The resulting crystallographic orientation shows significant improvement. All these phenomena improve the material quality and mechanical properties of the single crystal castings.

The research further shows that the aging processes do not improve either the crystallographic orientation or the material hardness of the casting. In fact, there is a reduction in the degree of crystallographic orientation. In addition, there is a significant reduction in hardness after the first aging stage to the as-cast level, improving after the second aging stage to close to the level achieved after the solution heat treatment stage.

ACKNOWLEDGMENTS

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6 BIOGRAPHY

Ekaterina Rzyankina obtained her Bachelor of Mechanical Engineering degree from the Ural State Technical University in Yekaterinburg, Russia, in 2010. She held a position at VSMPO-AVISMA (Ti - Mg Manufacturing company in Russia) as an engineer and thereafter obtained her Master of Technology degree in Mechanical Engineering in 2013 from Cape Pennsula University of Technology in Cape Town, South Africa.

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Performance Evaluation of Custom Manufactured WC-12wt%Co Abrasive Grinding Wheel

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Abstract
Grinding is a material removal process making use of geometrically nondefined tool edges, or abrasive particles, which is bonded together in the form of a grinding wheel to cut, or machine, a material into shape. The materials used as the abrasive is most commonly aluminium oxide or silicon carbide. These abrasives are normally bonded with a vitrified or resinoid bonding to form the grinding wheel. Grinding wheel applications typically range from wood and soft metal grinding to hard carbide steel and ceramic grinding. There is thus a gap in the variety of available grinding wheels for a multipurpose grinding wheel. This paper will explore the application of tungsten carbide (WC-12wt%Co) as an alternative abrasive material for a grinding wheel and will be bonded with inexpensive resin. Tungsten carbide falls in the cemented carbide family of hard materials, having a high hardness-to-toughness ratio. This is advantageous for the machining of titanium alloys and is the workpiece material. The paper will describe the process of custom manufacturing of the WC-12wt%Co grinding wheels for experimental purposes.

Keywords
Grinding, cemented carbide, titanium

1 INTRODUCTION

Grinding wheel usage date back many hundreds of years to when only simple hand-held tools were used due to the lack in machine tool technology. It's been utilised in manufacturing for more than 100 years. The 20th century saw the growing use of grinding wheels as a modern machining process, leading to scientific analysis and research of the grinding process [1].

The abrasives used in the production of grinding wheels have traditionally been the same for many years, mainly due to their successful performance characteristics and cost effectiveness. These abrasives are now being challenged by cemented tungsten carbide, which is harder and tougher than most traditional abrasives. WC-12wt%Co is used in this research work as abrasive medium in the production of mounted point grinding wheels. The performance characteristics of these custom manufactured mounted points are reported on, which is to some extent related to the effectiveness of their design and the manufacturing technique.

2 GRINDING

Grinding is the machining action of multiple abrasive grains on the face of a grinding wheel which resembles a complex cutting tool with cutting angles and voids for chip clearance. The abrasives are randomly shaped and arranged in the grinding wheel with the cutting edges undescribed with reference to a single particle, and thus nondefined. The wheels rotate at high rotational velocities to remove material from softer workpiece materials in large volumes with coarse and uneven surface finishes or in small volumes with smooth and fine surface finishes [2].

A grinding wheel consists of three main components; the abrasive grains, binder and filler. The filler material is very soft and acts as space keeper to create voids, but is not found in all grinding wheels. The voids are necessary for chip clearance and cooling of the grinding wheel. There are six main classifications for grinding wheels which are related to the shape of the produced surface (face, peripheral, thread, gear, profile and form grinding) of which peripheral grinding is used in this study [2], [3].

The size of abrasive grains are made from material having a grain size numeral of 8 (coarse, ± 2.8mm) up to 1200 (very fine, 0.003mm). The bonding medium produces extremely soft to extremely hard bonding strengths or grades. A resin bonding is used in this study, which is less sensitive to sudden temperature changes and shocks than vitrified bonded wheels [2].

Grinding wheel wear can take place in the abrasive grains or in the bonding material. The wear mechanisms are abrasive grain dulling or grain/bond breakage. When dulling occurs, flat wear areas are formed on the edges of the grinding surface, leading to increased grinding forces and elevated temperatures. This wear mechanism usually occurs when the wheel is submitted to gentle grinding conditions. When the grinding loads are higher, the abrasive/bond breakage wear mechanism will lead to higher volumetric wear and cause constant grinding forces and temperatures [3].

There are three important cutting edge angles for chip formation, which are clearance angle (α), rake angle (γ) and wedge angle (β). These angles can only be indicated with statistical parameters such as mean values or distributions, since a multitude of cutting edges are present in different orientations on any given surface. These angles can be seen in Figure 1 [3].

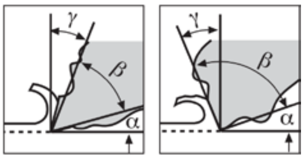

Figure 1 - Cutting edge angles imortant for chip formation [2].

A large amount of friction occurs between the grains and the workpiece during grinding. Almost all of the mechanical energy supplied for grinding is converted into heat due to the friction. Figure 2 shows the dissipation of mechanical input energy into various other output energies [3].

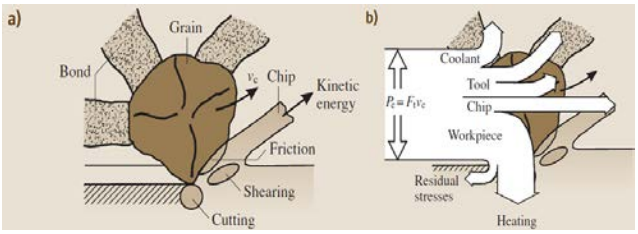

Figure 2 - Energy conversion; a) Effects of energy conversion, b) Energy flows [3].

Mechanical or thermal overstressing of the workpiece material may adversely affect its characteristics such as visible marks due to regenerative chatter, tensile residual stresses, surface hardening and even cracks [3].

3 WC-12WT%CO AS ABRASIVE MEDIUM

Tungsten carbide (WC) is a suitable material for wear and corrosion resistant applications due its high hardness and chemical stability. It has low toughness and is thus brittle. The toughness of WC is improved by adding a ductile metal, such as cobalt. The adding of cobalt shifts the category of WC-Co to that of a cemented carbide (or cermet), which has a good combination of hardness and toughness [4], [5].

Its application is extensive, ranging from cutting tools, rock-drilling bits, dies for powder metallurgy, wire drawing dies, and indenters for harness testers. WC-Co parts and components are commonly manufactured by compacting and sintering WC-Co powder into a desired geometry, or by thermally spraying the powder onto the outside of an already manufactured geometrical part.

The mechanical, thermal and tribological characteristics of WC-Co are greatly dependent on the cobalt content and WC particle size. The grain size of WC is typically in the range of 0.1µm to 10µm and cobalt content of between 3 and 30 wt% is used. The decreasing of WC grain size increases the hardness of WC-Co and an increase of cobalt content increases ductility. Although a decrease in grain size increases hardness, coarser grains of hardness 1000 – 1600 HV has shown greater wear resistance than smaller grains. The smaller grains thus do not always produce better wear resistance [6].

The WC-Co used in this study has 12wt% cobalt content and was acquired from Global Tungsten & Powders in the USA as their SX408 powder type. The WC-12wt%Co was acquired in powder form with particle size ranging from 10µm to 44µm and having a spherically agglomerated geometrical structure.

4 GRINDING WHEEL BINDER

Resins are thermosetting composite plastics in a polymer matrix. They do not produce solid reaction products and thus have low cure shrinkage. Epoxy resins have good adhesion to other materials, environmental and chemical resistance and chemical and insulating properties [7].

The most commonly used resin in the production of resinoid bonded grinding wheels is phenolic resin. For this study however, an epoxy resin is used. The tensile and compressive strength mechanical property of both resins are similar, as well as their respective preparation methods.

The major advantage phenolic resin has over epoxy resin is its slightly higher thermal decomposing temperature limit. The phenolic resin can thus withstand slightly higher temperatures than the epoxy resin. This will however not affect the research study as the temperatures reached during grinding is well above that of either resin's decomposing temperature threshold [8].

Phenolic resins contain phenols which are toxic, leading to strict exposure limits. They are also more expensive than epoxy resins. From a safety and economic point of view it becomes clear that epoxy resins are preferred for the production of custom grinding wheels [8].

The epoxy resin used in this study is the AR 600 brand with AH 2336 hardener system from Aerontec CC. It is a high performance epoxy resin with low viscosity, having a combination of good mechanical and thermal properties.

5 RESEARCH METHODOLOGY

5.1 Determination of resin content

The use of epoxy resin as binder in the manufacturing of mounted points poses the challenge of determining the optimal resin-to-binder ratio. It is suggested that the maximum resin content in a resin bonded grinding wheel should not exceed 30wt% if effective and functional grinding of the wheel is desired [9]. This amount of resin is based on the use of abrasive particles with a size range of 110µm - 150µm. Since the WC-12wt%Co powder used in this study is smaller (±46µm), the amount of resin will be less than the suggested maximum of 30wt%.

The reason for this lower resin content is due to the wetting effect the resin has on the abrasive particles. In the case of a large particle, more liquid resin is required to cover the entire particle's surface due to its relatively large surface area. When the smaller particles are used, less liquid resin is required to cover and wet the particle's relatively small surface area. The complete covering/wetting of a particle's surface area with resin is necessary to ensure the bonding of the particles to one another and to form a grinding wheel, or in this study, a mounted point.

The amount of resin in a grinding wheel can also affect its strength and grinding efficiency. Excessive resin with relatively small abrasive particles produces a strong grinding wheel, but the resin will prohibit the effectiveness of grinding. Conversely, if too little resin is added, the abrasive particles will be able to do the machining work effectively, but the wheel will not be strong enough to withstand the grinding forces. The strength and work effectiveness of the grinding wheel is thus dependent on the wheel's resin content.

The lowest resin content producing the strongest mounted points should thus be determined. The main stress during operation should first be determined and since the mounted points are spinning at high rotational velocities, the main stresses imparted on the mounted point will be due to centrifugal forces from spinning. By using rotating disc theory, the main stress during rotation can be determined. Figure 3 below indicates the mechanics during centrifugal loading.

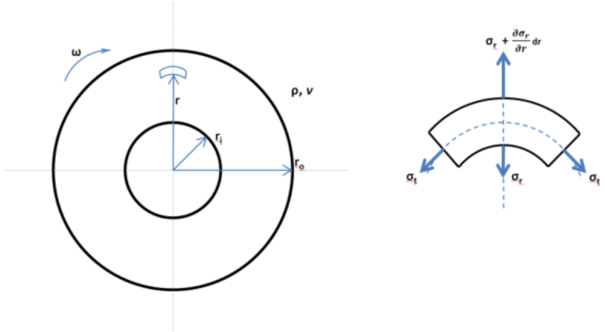

Figure 3 - Induced stresses during centrifugal loading of a rotating disc [8].

The disc has rotational angular velocity $\boldsymbol{\omega}$ (rad/s), relative composite density $\boldsymbol{\rho}$ (g/cm^3), Poisson's ratio $\boldsymbol{v}$ (dimensionless), inner radius $\boldsymbol{r_i}$ (m) and outer radius $\boldsymbol{r_o}$ (m). A section can be taken at any radial distance $\boldsymbol{r}$ from r_i to r_o where the stress equilibrium indicates the internal stresses. Stress in the radial direction is radial stress, $\boldsymbol{\sigma_r}$, while stresses along a circular path are tangential stress, $\boldsymbol{\sigma_t}$ [8].

For the given section, the tangential stress is equal in opposite directions, while the radial stress increases from the inner to outer radii of the section. These stresses can be calculated for a given radial distance between r_i and r_o with the following equations [10]–[12].

$$\sigma_r = \frac{3+v}{8}\rho\omega^2\left(r_i^2 + r_o^2 - \frac{r_i^2 r_o^2}{r^2} - r^2\right) \quad (1)$$

$$\sigma_t = \frac{3+v}{8}\rho\omega^2\left(r_i^2 + r_o^2 + \frac{r_i^2 r_o^2}{r^2} - \frac{1+3v}{3+v}r^2\right) \quad (2)$$

The composite density and Poisson's ratio is required, which can be calculated with Equation (3) and (4) with the variables as seen in Table 1 below.

	Density (g/cm^3)	Poisson's ratio	wt%	vol%
WC-12wt%Co	3.4	0.23	90	74
Resin	1.1	0.31	10	26

Table 1 - WC-12wt%Co and epoxy resin material characteristics [8].

$$\rho_{composite} = wt\%_{WC-12Co} \cdot \rho_{WC-12Co} + wt\%_{resin} \cdot \rho_{resin} \quad (3)$$

$$v_{composite} = vol\%_{WC-12Co} \cdot v_{WC-12Co} + vol\%_{resin} \cdot v_{resin} \quad (4)$$

The density of cemented tungsten carbide in Table 2 is that of its apparent powder density. The fully dense true density of WC-12wt%Co is 14.88g/cm^3. By implementing Equation (1)-(4) with the variable values in Table 2, the resulting stress distribution of Figure 4 can be generated along the radius of the mounted point for a sample containing 10wt% of resin.

Composite density (ρ_c)	3.17 g/cm^3	
Composite Poisson's ratio (v_c)	0.25	
Rotational speed (ω)	20 000 rpm	2094.39 rad/s
Inner radius (r_i)	0m	
Outer radius (r_o)	0.02m	

Table 2 - Tangential and radial stress calculation variables.

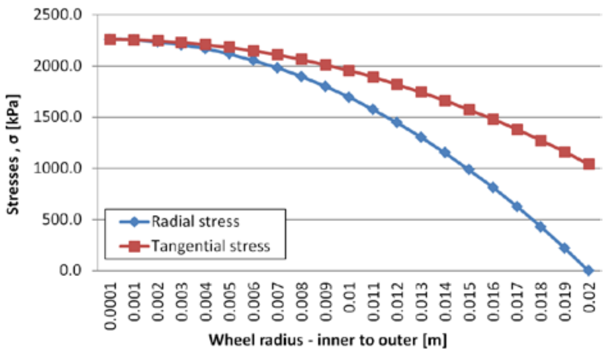

Figure 4 - Tangential and radial stress distribution along the radius of a mounted point [9].

The resulting stress distribution in Figure 4 indicates the major stress in a rotating mounted point is a tangential (tensile) stress. Thus the tensile strength of samples with various resin-to-abrasive ratios has to be tested. The structure of the resin-abrasive composite mixture resembles that of concrete or stone and thus the Brazilian Disk test can be used to determine its tensile strength.

The Brazilian Disk test is an indirect tensile strength test in which a disk-shaped sample is diametrically compressed to failure. This testing method assumes that failure of the disk samples will occur within the material at the point of maximum tensile stress. The failure point occurs at the centre of the disk where the tensile stress is greatest. As the disk is compressed from the top and bottom, a tensile force is applied to the central line trying to pull the sides away from each other. The testing orientation, loading direction and failure mode during the Brazilian Disk test can be seen in Figure 5 [13], [14].

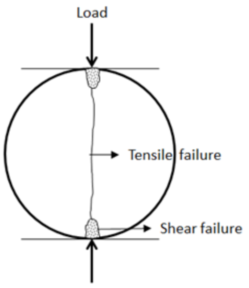

Figure 5 - Test sample orientation, loading direction and failure mode during the Brazilian Disk test [13].

Samples in the form of a 30mm diameter disk were made containing 10wt%, 12wt%, 14wt% and 16wt% resin. They were compressed unto failure and the failure pressure recorded. Figure 6 shows the four disks after failure. Note the upper and lower loading points (flattened area on outside periphery of disks), shear failure area (triangular failure section adjacent to loading points) and central crack.

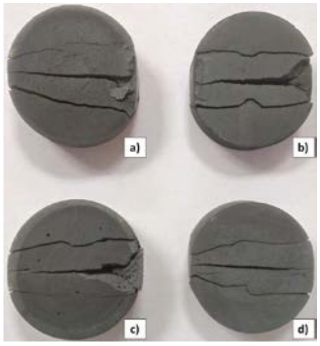

Figure 6 - Brazilian Disks test specimens after failure: a) 10wt%; b) 12wt%; c) 14wt%; d) 16wt%.

The tensile strength of the samples is calculated with Equation (5) below.

$$\sigma_t = 0.636\frac{P}{Dt} \qquad (5)$$

In Equation (5) ***P*** represents the applied load at failure (N), ***D*** the diameter of the disk (m) and ***t*** the thickness of the disk (m). The variables for each tested sample and its respective tensile strength can be seen in Table 3. Figure 7 depicts the tensile strength of the samples graphically.

	10wt%	**12wt%**	**14wt%**	**16wt%**
Disc thickness (mm)	8.94	9.5	9.9	11.6
Load at Failure (N)	188	214	321	374.5
Tensile strength (kPa)	445.86	477.75	687.74	684.55

Table 3 - Brazilian Disk test samples thickness, load at failure and tensile strength.

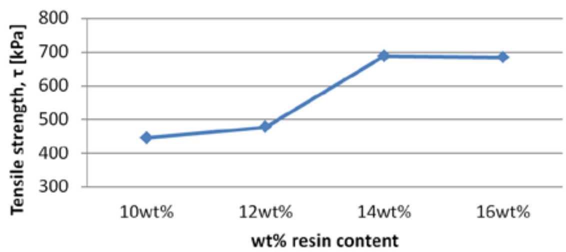

Figure 7 - Resulting tensile strength of resin-abrasive composite material [8].

From these results, the 12wt% and 16wt% resin contents were chosen for mounted point production. The 12wt% resin content is chosen for its slight strength advantage over that of the 10wt% resin content, as well as its lower resin content compared to the 14wt% and 16wt% resin content samples. The 16wt% resin content is chosen for its high strength, as well as its internal structure. The internal structure of this sample contains many air pockets, which is beneficial to the grinding process in that it helps to remove heat and grinding swarf from the area being grinded.

The comparison of the internal structures of the 12wt% and 16wt% resin content samples can be seen in Figure 8.

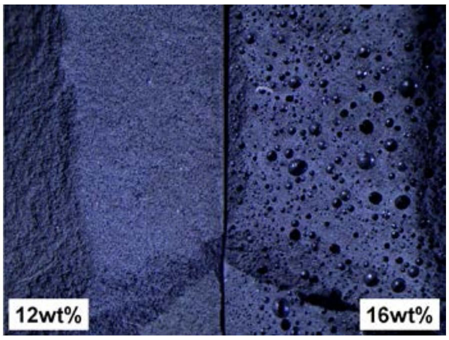

Figure 8 - Internal structure of the 12wt% and 16wt% resin content samples.

5.2 Mould design and mounted point production

The mounted points are produced in a mould with specific geometrical dimensions. These dimensions are important to ensure consistency of produced mounted points and accuracy of grinding. The design of the mounted points is a combination of W185 and W202 mounted points from the ISO 603-17 standards document.

The mounted points have a central stainless steel spindle onto which the resin-abrasive composite is bonded. The mould for producing the mounted points consists of a base plate onto which the main mould body is bolted and an end cap to stabilize the top part of the spindle while the resin is curing. The mould will produce a mounted point with diameter 20mm, height of 13mm and a spindle diameter of 3mm. The assembly of the mould can be seen in Figure 9.

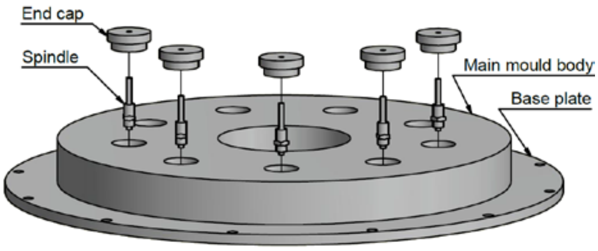

Figure 9 - Mould assembly for the manufacturing of custom mounted point grinding wheels.

The resin and abrasive powder is mixed prior to moulding in specific quantities to produce a 12wt% or 16wt% resin content. This mixture is placed in the mould and left to pre-cure at ambient room temperature for a minimum of 12 hours. After this pre-curing stage, the entire mould is placed in a hot box thermal resin curing oven to thermally cure the resin-abrasive composite to maximum strength. The process takes place at 80^{o}C for 2 hours, followed by 150^{o}C for 3 hours and finally at 180^{o}C for 4 hours.

The hot box oven is switched off after the 9 hours and the mould left inside to slowly cool to ambient room temperatures. At this stage the resin is fully cured and the mounted point(s) can be removed from the mould. Figure 10 shows a cross section of the setup of the mould with cured resin-abrasive composite.

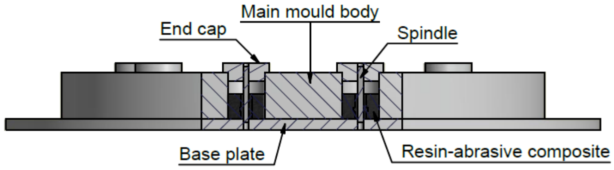

Figure 10 - Cross section of mould setup before mounted point removal.

5.3 Experimental design and setup

To determine the performance of the resin-abrasive ratios and the manufacturing process to produce the mounted points, the manufactured points is to grind a workpiece material and characteristics measured. The performance of the mounted points is characterized by the wear rate of the point, the workpiece material surface integrity and surface finish. The chosen workpiece material for experimental testing of the mounted points is Ti6Al4V. This titanium alloy is both hard and tough and has a unique strength-to-weight ratio [15].

For the experimental tests, only two variables are changed; spindle rotational speed and traversing feedrate of the mounted points. All mounted points for experimentation are manufactured with the same size abrasive particles. During grinding, the depth of cut for each grinding pass will stay constant and thus the perpendicularly applied grinding force as well. The transverse grinding force will change due to the different combinations of spindle speed, feedrate and resin content.

Each variable is changed between three values. For each combination of spindle speed and feedrate, only one mounted point will be used to ensure consistency and that each data set starts with the same initial diameter and with the same surface finish and texture. Also, at each variable combination, each mounted point will be tested three times to ensure statistical consistency of data. Each variable is independent of one other and has three values which are tested.

The amount of experimental grinding passes adds up to 54; 2 different resin contents, 9 variable combinations and 3 runs per mounted point. The value range of spindle speed and feedrate can be seen in Table 4.

Spindle speed, *v*	[RPM]	15 000 – 20 000
Feedrate, *f*	[mm/min]	30 - 90
WC-12wt%Co content	wt%	12, 16

Table 4 - Randomized execution order for mounted point experiments.

Grinding is done on a 3-axis CNC micro machining machine that is computer controllable. A Dremel 4000 multi-tool with variable speed control is used to drive the mounted points. The titanium alloy workpiece is placed in the machine, levelled and clamped in place. The machine controller software is calibrated and the zero-point indicated for positional referencing of the system. The g-code for controlling the movement path of the machine is imported into the software. The zero-point of the system and the implemented g-code can be seen in Figure 11 and Figure 12.

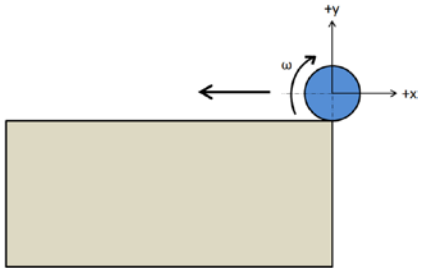

Figure 11 - Zero-point positional indication (viewing direction from above) [8].

```
G90
G01 X0 Y0 Z0 F1100
G01 X0 Y30 Z0 F1100
G01 X0 Y30 Z-5 F1100
G01 X0 Y1 Z-5 F600
G01 X0 Y-0.1 Z-5 F80
G01 X-102 Y0.4 Z-5 F60
G01 X-102 Y30 Z-5 F1100
G00 Z40

M30
%
```

Figure 12 - G-code implemented in computer software to control mounted point movement [8].

The depth of cut is 100 µm. This value is adjusted with 100µm for each grinding pass of the same mounted point to ensure the depth of cut stays constant at each pass. This means that for the second machining pass, the depth of cut will be 200µm from the zero reference point to produce a 100µm cut over the already 100µm deep first cut. Similarly, the third grinding pass depth of cut is adjusted in the same way.

The experiments were conducted without lubricating and cooling fluids. These fluids are known to affect the grinding performance of grinding wheels in both positive and negative ways. It was decided to not make use of these fluids for the main purpose of determining the effect of the mounted points under dry conditions. It is however wise to use cooling fluids during machining of titanium alloys because of the reactivity of titanium at elevated temperatures. It is thus suggested to use these fluids in future work.

The mounted points are securely fixed to the Dremel. A vacuum is used to suck up the grinding dust (extractor close to the mounted point). The experimental setup can be seen in Figure 13 and Figure 14.

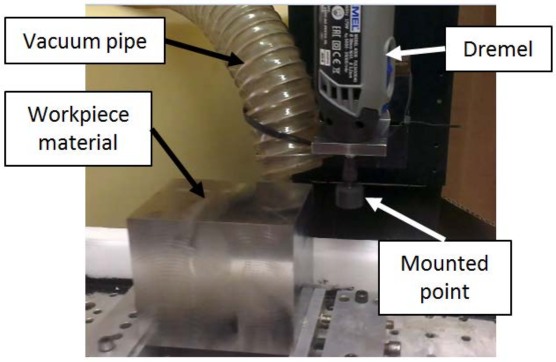

Figure 13 - Titanium alloy workpiece material clamped in position with mounted point securely fixed in the Dremel.

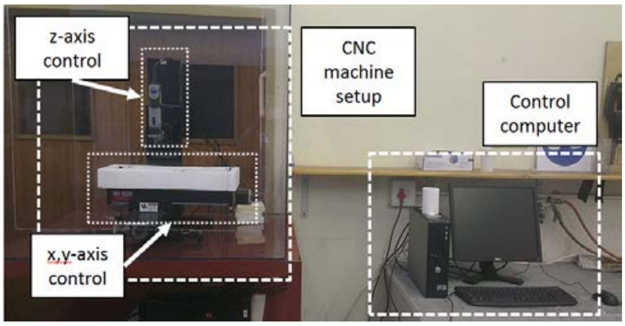

Figure 14 - CNC micro machining setup (left) with control computer (right).

5.4 Data acquisition

Machining data is recorded and measured to determine effectiveness of grinding. The rate of wear of the mounted points is determined as a change in volume. The change in volume is calculated by measuring the change in diameter of the mounted point after each grinding pass. This is done with the use of a coordinate measuring machine (CMM).

The CMM's software is programmed to automatically measure multiple circles on the periphery of the mounted point from top to bottom. This set of measurements is used to incrementally calculate the volume of the mounted point. This measuring process is conducted after every grinding pass and thus for 54 total sets of diametral data collected.

The integrity of the workpiece material's surface refers to the effect grinding forces and thermal exposure has on the surface of the material. It is determined by the measurement of the micro hardness of the surface of the workpiece material. A change in hardness indicates a structural change and possible integrity compromise. The rise in hardness could also lead to micro cracks and/or crack initiation areas. The micro hardness of the workpiece material is measured on multiple points along the grinding path after grinding.

The surface finish of the workpiece material indicates the efficiency of the abrasive particles to remove material. The grinding process used for testing the mounted points is a micro grinding process, and thus the surface finish should be smooth after material removal. The method for testing the surface finish is by measuring the surface roughness of the workpiece material with a surface roughness tester at the end of grinding.

The measured data is processed, compiled and is discussed in the following section.

6 EXPERIMENTAL RESULTS & DISCUSSION

During the execution of the experiments, three mounted points failed and was completely destroyed. These three mounted points all contain 12wt% resin and was manufactured with/during the same process. Mounted point #4 and #7 had the same spindle speed, but different feed rates, while #7 and #8 had the same feed rates, but different spindle speed. Mounted point #4 and #8 has no parameters in common, except resin content and depth of cut. The reason for failure can thus not be attributed to the set of parameters.

The wear of all mounted points are shown in Figure 15 as the cumulative amount of volume lost. The data for the three failed mounted points are not included as it is considered as outlier data point. The wear is determined by calculating the amount of volume of grinding composite material worn after a grinding pass with the change in diameter measurements. Figure 15 shows all mounted point wear data of less than 300 cm^3, with the 12wt% as solid lines and the 16wt% as dashed lines. From the graph it can be seen that the amount of resin does not have a definite influence on the wear of mounted points. The rate of wear is thus more dependent on the spindle speed or feedrate.

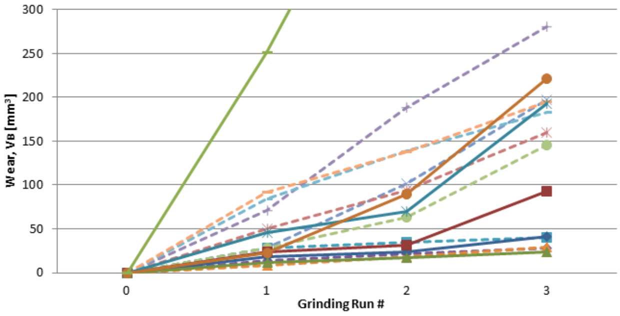

Figure 15 - Measured wear of mounted points after three grinding passes.

The surface roughness (R_a) of the workpiece material is expected to be of higher quality after grinding. The surface roughness was measured on multiple points before grinding took place, as well as on areas where grinding would not take place, and the average R_a value calculated. After all grinding passes were completed, the surface roughness was measured of every area where grinding took place and again an average R_a value calculated from multiple measurements. The average R_a measurements of the pre- and post-grinded surfaces can be seen in Figure 16. The measured data shows that about 66% of the mounted points produced a higher quality surface roughness by having a R_a value less than the non-grinded surface, which is an improvement.

The micro hardness measurements were done similarly to the surface roughness. Multiple measurements were taken on the pre- and post-grinded surfaces. This data is shown in Figure 17. Except for three mounted points, all grinding produced a harder surface than the non-grinded material surface. This is expected as grinding induces stresses on the material being grinded due to frictional heat, changing the micro structure of the surface of the grinded material.

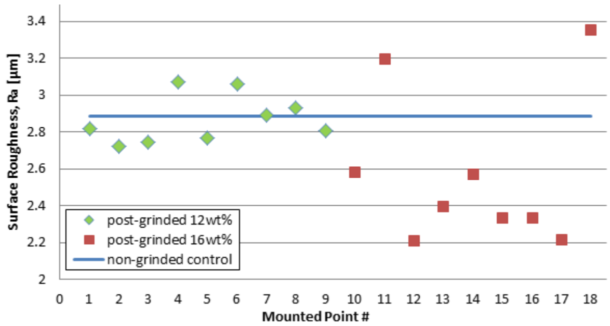

Figure 16 - Average surface roughness prior to and after grinding.

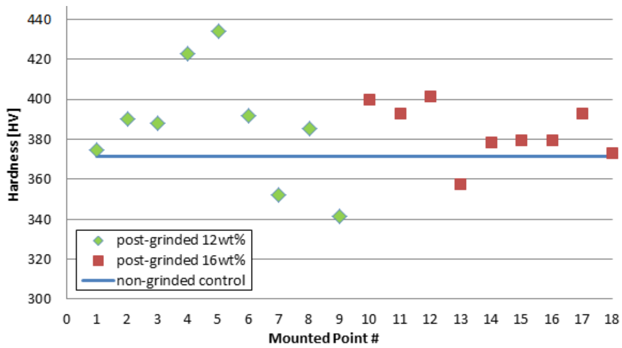

Figure 17 - Surface micro hardness prior to and after grinding.

For both Figure 16 and Figure 17 the average pre-grinding data is shown as the solid blue line. The average measured post-grinding data is shown as dots, green diamonds representing the 12wt% samples while the red squares represents the 16wt% samples.

7 CONCLUSION

The custom manufactured mounted point grinding wheels performed similar to conventional grinding wheels. It also removed material during the micro grinding process, produced on average higher quality surface finishes and caused work hardening of the workpiece material surface. The design and manufacturing process was thus successful and can be applied for future production of mounted points, but improvements can always be implemented.

It is recommended that the manufacturing process be revised and improved for automation purposes. Instead of using epoxy resin, a phenolic resin can be used to examine its influence on the performance of the mounted points.

Larger abrasive particles can also be used to determine the effect grain size has on the production process and on grinding performance of mounted points.

8 ACKNOWLEDGEMENTS

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10 BIOGRAPHY

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Experimental Investigation of the Influence of External Forces on Ultrasonic Parameters for Ultrasonic-Assisted Turning

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Abstract

A possible application of ultrasonic-assisted machining is the highly productive manufacturing of surface microstructures in turning processes. This paper refers to parameters required to create hemispherical-shaped micro dimples within the surface of metal parts during a turning process. In one possible application these micro dimples can be used as oil pockets in sliding elements. Out of the equation of motion an influence of the cutting forces can be expected. This paper describes investigations on the influence of external forces on ultrasonic parameters for ultrasonic-assisted turning. It is expected that the amplitudes of the ultrasonic transducer, an actuator vibrating with resonance frequency, decrease as a result of loading due to cutting forces. A test stand was developed for a discrete analysis of the influence of the cutting forces. It allows applying defined forces to the ultrasonic system. Results of measurements contribute to a better understanding of the influence of the processing forces on the ultrasonic system.

Keywords

ultrasound, external force, microstructure

1 INTRODUCTION

Nowadays ultrasound in manufacturing is used in many applications. Ultrasound can reduce process force, improve fluid fluctuation, generate levitation and reduce manufacturing time.

The production of micro dimples for oil reservation increases the tribological properties of the surfaces. This kind of microstructuring was already used in turning process at low frequency. A frequency increase makes it possible to produce more micro dimple in the same time. It results in a decrease of the manufacturing time and reduces the process costs.

2 STATE OF THE ART

2.1 Methods for creation of microstructures, with separately considered vibration assisted process

There are many ways to create microstructures on machined surfaces. In comparison to different manufacturing techniques the cutting process provides a great potential, because of higher machinability, geometrical precision and lower elements costs in generating microstructures. There are two principles for the production of microdimples through cutting process. Non-resonant systems oscillate out of the eigenfrequency of the system. This allows the creation of various surface shapes as well as surface microstructures. Non-resonant systems, called also Fast-Tool-Servos, are an object of investigations [1, 2]. The great disadvantage of this system is the limited amplitude. Resonant systems bypass this disadvantage through the usage of the resonance frequency. This means, the excitation frequency is equal to the eigenfrequency of the system. The result is a higher amplitude as with non-resonant systems. The adverse effect of resonant systems is that the possible movements depends on the eigenmodes of the system.

The initial works at the TU Chemnitz provide a possibility of producing microstructures by ultrasonic-assisted turning with a resonant system [3, 4]. The focus lied on experimental studies to enhance knowledge about process parameters. A significant challenge in the usage of the turning process in microstructures production is the emergence of the small peak features which appear at the edge of the structure (Figure 1). This feature can be decreased using proper process parameters, but it cannot be completely avoided.

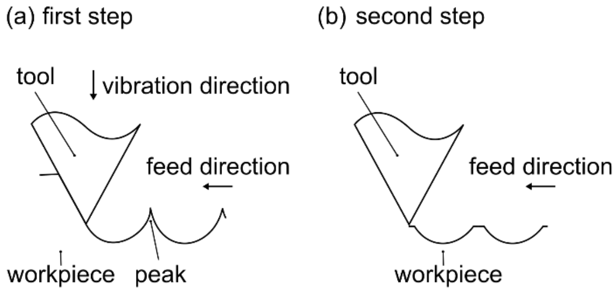

Figure 1 - Principle of the microstructuring process, a) first cutting stage; b) second cutting stage (without vibration)

Technological possibility to eliminate that feature is the usage of two stages turning process [4]. During the first stage of turning, the ultrasonic-assisted turning tool creates the microstructure. Therefore it uses an additionally vibration movement in the direction orthogonal to the front or shell surface of the cylindrical workpiece. During the second stage, cutting takes place without the vibration support. The tool remachines again the surface to remove the peaks. This results in plateau shaped micro-dimpled surface. Figure 1 shows the principle of the process. The disadvantage of this process is that the depth of micro dimple is decreased during the second stage of the process. The highest depth of a micro dimple achieved after the second stage of turning is about 4 µm [4]. This insufficient depth would not outlast the initial surface wear. Regarding this wear, it is necessary to predict the microstructure geometry (including its depth) as accurate as possible. The first step of this analysis includes the kinematic simulation (using Matlab), which would neglect the tool wear and material stiffness [4]. A neglected point is also the behavior of ultrasonic system under the action of external forces.

2.2 Influence analysis of external loads acting in ultrasonic system

The ultrasonic system consists of a transducer and a horn. The transducer is an actuator, which oscillates in resonance. The horn is a mechanical transformer, which influence the amplitude by changing the cross area. Basics of the influence of external forces on ultrasonic system were established and are known since 1951 [5]. The test stand, which was used in this article, consists of the ultrasonic system, steel ball, connecting rod, sensor and weight. It is presented in Figure 2 (a).

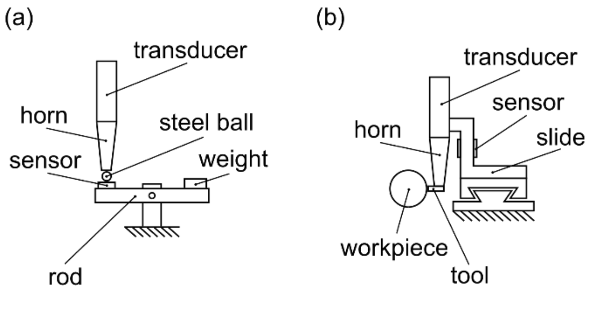

Figure 2 - Test stand (a) design of Mason and Wick [5], (b) design of Astashev and Babitsky [6]

In Figure 2 (a) the sensor lies on an edge of the rod and the defined weight on the other. This design allows simulating the external force acting on the ultrasonic system by change of the weight. The analysis examines connection between the preload force, weight force and amplitude of applied vibrations. Important findings in the article from Mason and Wick are that with the increase of preload force the contact stiffness will increase. If the amplitude increases, the contact stiffness will decrease. Furthermore, the maximum contact force increases, with the increase of amplitude and preload force. The disadvantage of that design is the usage of weights to generate external load. Only in a case of elastic rod, reduced Kelvin-Voigt model can be assumed. In the other case a higher mass oscillator would be the result. Besides, it behaves in the process more like a uniaxial compressive load, therefore, a deformation of the material instead of cutting takes place.

In the further work the process forces in the direction parallel to the cutting direction in vibration supported turning were examined [6]. The design presented in Figure 2 (b) was used. The concept of this work lies in the reduction of the cutting force by ultrasonic vibrations, not in the creation of microstructures. A significant result of this study is the determined dependence between resonance frequency and cutting speed. Furthermore, it shows that cutting force increases with the increase of the turning speed. The disadvantage of the work done in that field lies in the fact that only averaged forces and not the detailed force behavior was investigated. The ultrasonic direction was tangential to the workpiece surface. By microstructuring the ultrasonic direction is radial to the workpiece surface. Therefore, the results seem non-transferable of the force behavior in microstructuring.

The analysis of the test stands and analysis technics conducted by the different reasearch groups, lead to the conclusion that the influence of the external forces on the ultrasonic system has never been examined in the field of ultrasonicly supported turning, designed for microstructures creation. For this reason, the next step in that analysis should be a creation of test stand, which allows such measurement.

3 TEST STAND DESIGN

3.1 Comparison of different concepts

The main task of the test stand is to define static forces equal to 400 N, related to the force data from previous work [7]. External forces should act in all 3 directions, based on machining forces which appear during turning, as presented in Figure 3 (a).

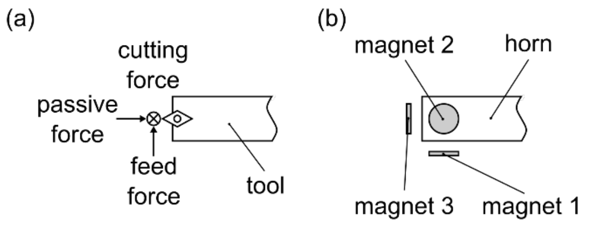

Figure 3 - (a) force components generated by cutting process, (b) imitation of forces through magnets

Folllowing concepts of implying external load were created:

1. Force due to weight
2. Force applied due to piezoelectric actuators
3. Force generated by air pressure

4. Force generated by magnetic field

Force applied by the weight makes the construction easy, however leads to the higher mass oscillations as a reduced system. Piezoelectric actuators can achieve high dynamic forces. Significant problem in this design is the contact between the horn and the actuator. High frequencies generate high friction what consequently leads to high temperature. The contactless assumption should solve that problem hence, air pressure force was proposed. The preliminary tests were carried out with an electronic scale and different pipe diameters at the air pressure supplied system. Unfortunately previously defined forces were not achieved in this way. During the preliminary tests, the air pressure equal to 8 bar, with the inner diameter of the pipe of 7.5 mm generated only 29 N force. The last concept assumes using a magnet force. It allows generation of much greater forces than the air pressure, therefore, from all concepts the final one was chosen.

3.2 Implemented concept

The chosen concept uses three neodymium magnets to generate the external force in all 3 directions. It is presented in Figure 3 (b). The distance between horn and magnet influences the force directly. Setting of the distance is achieved through a threads connection at the end of the magnets. For the chosen concept the horn must be designed out of a magnetic material. This point was essential since Ti6Al4V alloy, the standard material for high power ultrasonic systems, is not a magnetic material. Therefore, steel horn of C45 was created. Also the design was simulated to determine dimension of the horn. The key target was a resonance frequency of 20 kHz. Material properties of modulus of elasticity of 2e+5 N/mm², poisons ratio of 0.3, density of 7.85 t/m^3 were used. The horn length was calculated to be equal to 126.5 mm. Horn was manufactured on such a way, that firstly longer length of this part was manufactured to examine its natural frequency, than the length was decreased, and frequency measurement was repeated. This procedure was done until the length of the horn causes natural frequency to be equal to 20 kHz.

4 CALIBRATION OF THE TEST STAND

4.1 Preliminary test concept

Calibration of the magnetic force acting on the steel horn was made by a tensile test in a universal test machine. Force measurement may be done for the forces not higher than 5 kN. The test stand design is presented in Figure 4.

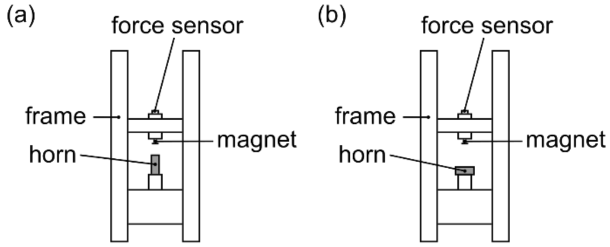

Figure 4 - Calibration test with the universal test machine to investigate relationship between the magnet force and distance between the magnet and (a) front face of the horn, (b) shell surface of horn

The test stand was designed in such a way that the magnet is fixed by a screw, therefore it is easy to change the distance between the magnet and the horn. The setup procedure consists of 2 steps. First the test machine was moved until the magnet and the horn were in contact but the test machine measured the magnet force (tensile force) now. In the second step the screw was turned until the measured force was equal to zero because of the initiated pressure force. The result of this step is a balance of forces between pressure force and magnet force. The measurement had been carried out until a value of 4 % of maximal force was achieved. Measurements were made both for front and shell surface, where different intensity of magnetic field exists. The magnetic field also depends on the type of magnets in the system, thus all magnets were analyzed. Measurements for magnet and surface were repeated 5 times.

4.2 Analysis of preliminary tests

Results of calibration are functions of distance between horn and magnet and magnetic force. Example of obtained results is presented in Figure 5. The other functions are similar to the presented one.

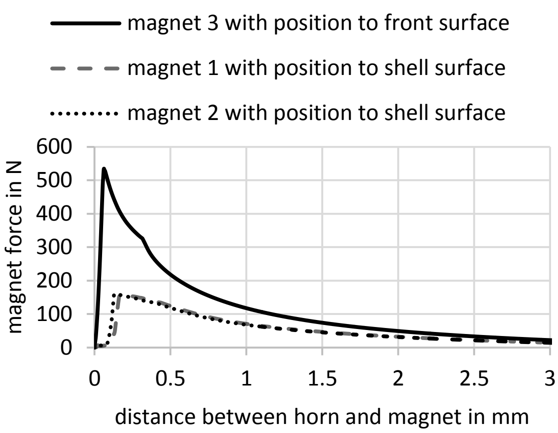

Figure 5 - selected results of the calibration tests between the magnet force and the distance

During the examination on the shell surface as well as the front surface the force increases very rapidly in the beginning. However, after reaching its maximum the force decreases with the increase in distance. The reason of this behavior lies in the preload from the calibration procedure. For the calculation of the distance between the horn and the magnet only the range from the maximum force are considered. After reaching the maximal value magnetic force decreases in a way very comparable to a negative exponential function. This data was used for the derivation of defined force cases. Shell surface force of 100 N, 80 N, 60 N and 40 N was analyzed in the experiment. In case of the front surface analyzed forces reached 200 N, 150 N, 100 N and 50 N. The assumption of the linearization from 0.5 mm distance between the horn and the magnet is acceptable because a change of the distance form 0.01 mm involves a deviation of only 1 N. The highest standard deviation from given points was equal to 1.35 N, this value also showed high repeatability.

5 INFLUENCE OF THE EXTERNAL LOADS ON THE ULTRASONIC SYSTEM

5.1 Experiment design

The test stand is presented in Figure 6. A vibrometer was used to measure oscillation amplitude and resonance frequency of the system.

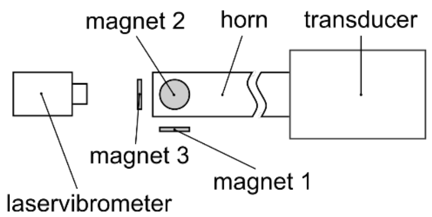

Figure 6 – schematic test stand

The test stand uses an ultrasonic transducer UIP-2000hdT from Hielscher Ultrasonics GmbH with a power output equal to 2000 W. This transducer was fixed to the frame by a nodal point with zero amplitude. Magnets were also fixed to the frame. The distance between the magnets and the horn was controlled by a feeler gauge, which allowed a dissolution in micrometer steps.

Firstly, the test stand was set in such a way, that it was possible to control the position of vibrations. Vibrations should have appeared only on the horn and should have not been found on the magnet or the connection between the frame and the ultrasonic system. The amplitude was measured on the front surface of the horn, on back side of magnet 3 and on the connecting point between the ultrasonic system and the frame.

In the first part of the experiment, uniaxial load with different magnitude was used. The amplitude and the resonance frequency were measured. The measurement was carried out in the direction orthogonal to the front surface. In the second part, the tests are repeated with the external forces in two and three directions.

5.2 Test evaluation

The measured amplitude of magnet 3 with 200 N magnetic force applied was equal to 0 µm. The movement of the connection point between the ultrasonic system and frame was found to be equal to 0.35 µm – such a low value might be neglected in further analysis. This low displacement proved that the test stand was applicable for the force measurement.

The oscillation amplitude caused by uniaxial force, was independent from its force value and was always around 6 µm. A resonance frequency of 19.6 kHz was also found for each force value. Increase in amplitude to 14.3 µm also did not affect any of the parameters - amplitude and resonance frequency remain constant. It was possible to conduct that analysis with higher amplitude only for a short period. High increase of temperature due to internal friction was observed. To analyze an amplitude higher than this one, material with lower internal friction needs to be used. The analysis of the forces influence on the ultrasonic system, using two or three directional forces, leads to the conclusion, that the force in considered range and reduction of static force has no influence on the ultrasonic system. This result actually contradicts the equation of motion. The influence of the external force in its range is a non-measurable value, therefore was not observed. This non-measurable influence is probably a result of the acceleration forces, which appear in the ultrasonic system and are much higher than the magnetic forces. That is probably the reason, why the change in the amplitude was not observed during measurements. It leads to the conclusion that, with proposed configuration, the measurement of the external forces' influence acting on the ultrasonic system is not possible. The use of a stronger magnet or a less powered ultrasonic system should help solving this issue. A significant result of this investigation is that the external forces, measured during ultrasonic-assisted turning, don't influence the working parameters of the used ultrasonic system. Further experiments on the microstructure production in turning will be continued with a special device, that integrates the considered ultrasonic system in the turning process. The construction is presented in Figure 7.

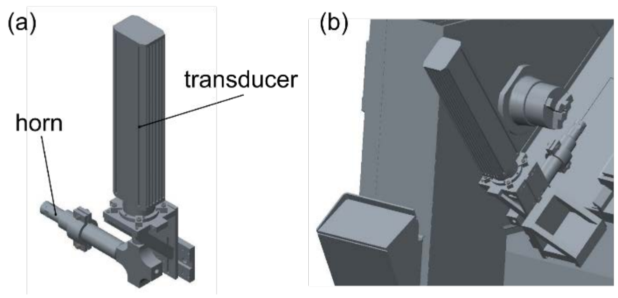

Figure 7 - (a) ultrasonic system for microstructuring, (b) turning machine with integrated ultrasonic system

6 CONCLUSIONS

The presented results lead to following results:

- The test stand used in the analysis is capable of applying defined external forces in three different directions.
- Uniaxial external forces with magnitudes up to 200 N have no influence on the ultrasonic system.
- Three loads defined at the same time in all considered directions with magnitudes equal to 200 N and twice 120 N also have no influence on the system.

The experiments showed that the ultrasonic parameters of the analyzed ultrasonic system are independent of external loads, which are typically measured during ultrasonic-assisted turning. Moreover, using the newly developed test stand allows the experiments with different ultrasonic systems. Furthermore, future analyses with stronger magnets acting on the given ultrasonic system will be possible.

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8 BIOGRAPHY

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Effective Methods for Learning Functional Safety within Automated Manufacturing Systems

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Abstract

Nowadays, almost all industrial processes incorporate electrical and electronic devices and systems. Many of these could cause severe harm to workers or the environment if not for special integrated safety features. Functional safety is thus aimed at all who design, manufacture, use, maintain, modify, manage or inspect machinery. It begins by helping manufacturers to systematically identify all possible risks associated with their machines or products throughout the machines entire life-cycle and makes recommendations on how these risks can be reduced to tolerable levels through the addition of safety features such as safeguarding, presence sensing, interlocking and computer diagnostics. Functional Safety is applicable to almost all areas of industry including the oil and gas industry, the manufacturing and transportation sectors and nuclear plants just to name a few. In order to force machine manufacturers to conform to safety standards, international trade organizations have imposed various technical trade barriers that restrict the movement of goods in certain areas unless it can be proven that the goods meet the required standards. This paper reviews various aspects of Functional Safety in the machine design phase including the procedures used in determining and eliminating risk according to EN ISO 12100, calculating various safety parameters such as the required Performance Level (PL) and Safety Integrity Level (SIL) and methods used for verifying and comparing the achieved safety levels according to IEC 61508 and IEC 62061. The design of suitable safety circuits according to EN 954-1 and its predecessor EN ISO 13849-1 is also examined. The paper goes further to discuss the role of Programmable Logic Controllers (PLCs) in achieving an acceptable safety level within machines as well as the importance of 'safe' communication. Also, because a large percentage of accidents in industry are caused by poor staff training, an effective step-by-step method for functional safety training that is aimed at giving learners a thorough - hands on – understanding of safety standards is highlighted. Finally, a case study is presented that reviews safety concepts within an Automated Guided Vehicle (AGV).

Keywords

Programmable Logic Controllers, Functional Safety Standards, Educational Systems, Automated Manufacturing Systems, Autonomous Guided Vehicle.

1 INTRODUCTION

In modern times, in order to compete on a global scale, industries all over the world are finding themselves under increasing pressure to make use of complex computerized systems in order to reduce their production costs while also improving the quality and quantity of their products. In many cases, these computerized processes involve vast amounts of energy which have the potential for devastating accidents. Reliable, well-engineered safety systems that are designed with a systematic approach are thus essential for protection against destruction and loss of life.

Up until the 1980's, the management of safety in hazardous processes was left up to individual companies. It was usually the responsibility of plant engineers to develop suitable in-house safety guidelines for certain processes based on a combination of 'best practices' and national regulations. More recently, many of these industry guidelines have matured into international standards which, when complied with, have potential to open greater opportunities for international trade. Government regulatory bodies in nations all over the world are thus seeing the benefit of enforcing laws that require conformance to specific safety standards [1].

Safety, as far as the control systems for machinery is concerned, is one of the most rapidly growing areas in the field of industrial automation. New and improved safety technology and strategies offer manufacturers a way of improving their productivity and competitiveness in the market. Safety is now commonly viewed as an integrated part of machine functionality rather than a mere facet added to meet regulations [2].

This paper reviews various aspects of Functional Safety in the machine design phase including the procedures used in determining and eliminating risk associated with machines according to EN ISO 12100, calculating various safety parameters such as the required Performance Level (PL) and Safety

Integrity Level (SIL) and methods used for verifying and comparing the achieved safety levels according to IEC 61508 and IEC 62061. The design of suitable safety circuits according to EN 954-1 and EN ISO 13849-1 is also examined. The paper goes further to discuss the role of Programmable Logic Controllers (PLCs) in achieving acceptable safety levels within machines as well as the importance of effective functional safety training that gives learners a thorough practical understanding of the relevant safety standards.

2 FUNCTIONAL SAFETY

Functional safety describes the aspect of safety that is associated with the functioning of any device or system that is intended to provide safety functionality. It is part of the overall safety of a system and generally focuses on electronics and related software by ensuring that it works correctly in response to commands it receives [1, 3]. Krosigk [4], in his work, describes functional safety as the ability of the safety related control system to function according to specification even with the occurrence of a failure so that the plant or machine remains in a safe state or is transitioned in to a safe state in order to effectively reduce the consequences of the failure. Figure 1 below depicts how functional safety makes a contribution to the overall safety of a system.

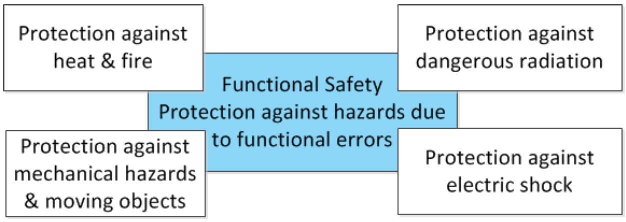

Figure 1 - Overall safety

Functional safety is thus aimed at all who design, manufacture, use, maintain, modify, manage or inspect machinery. It begins by helping manufacturers systematically identify all possible risks associated with their machines or products throughout the machines entire life-cycle and makes recommendations on how these risks can be reduced to tolerable levels through the addition of safety features such as safeguarding, presence sensing, interlocking and computer diagnostics. Functional Safety is applicable to almost all areas of industry including the oil and gas industry, the manufacturing and transportation sectors and nuclear plants just to name a few.

2.1 Causes of control system failures

In their publication on why control systems fail, the UK Health and Safety Executive (HSE) [5] reveal (as depicted in Figure 2 below) that specification errors, mostly attributed to inadequacies in the specification of the control system (due to poor hazard analysis of the equipment under control or to inadequate assessment of the impact of failure) dominate as the leading cause of accidents. From their analyses of incidents in the UK, the HSE showed that situations that lead to failure were often missed through the lack of a 'systematic approach' in the design, implementation, operation or maintenance phases of safety related systems.

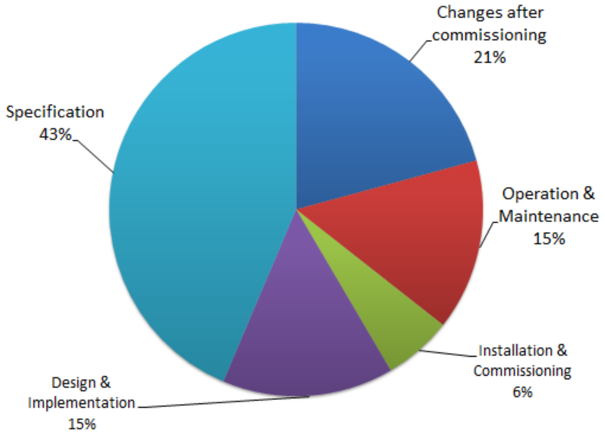

Figure 2 - Causes of control system failures

Majority of incidents could have been anticipated and even avoided if a systematic risk-based approach had been used throughout the life cycle of the system.

It was industry's inherent need for guidelines to achieve a systematic approach to machine design, implementation and on-going operation and maintenance that gave rise to the development of many of the Functional Safety standards that are in use today. These standards are able to thoroughly interrogate every phase of a machines life cycle and ultimately provide a tangible sense of quality assurance that benefits both manufacturer and consumer alike. Figure 3 shows how a systematic approach may be used to achieve quality assurance throughout the entire life cycle of a machine.

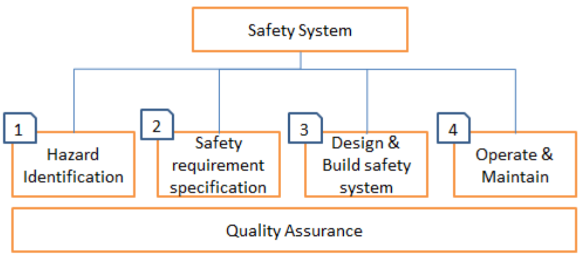

Figure 3 - Systematic approach to a safety system showing entire life cycle

2.2 EU Directives & Legislation

In order to promote an open market within the European Union (EU), all member states are obliged to enact legislation that defines essential safety requirements for machinery and its use. Machinery that does not meet these requirements cannot be supplied in to or within EEA countries.

Numerous European directives exist that can apply to the safety of industrial machinery and equipment, however, the Machinery Directive is the most relevant to functional safety. It deals with the supply of new machinery and other equipment including safety components. In order to trade freely within the EU, manufacturers of machines must ensure that their products conform to the requirements of the Directive. A summary of the requirements include:

- Ensuring that the applicable Essential Health and safety Requirements (EHSR) contained in Annex 1 of the directive are fulfilled.
- The preparation of a technical file that contains drawings, calculations, a list of standards used etc.
- Appropriate conformity assessment is carried out.
- An EC declaration of conformity.
- Instructions for safe use.

Current Harmonized European standards that are based on the Directive are set out by standards bodies such as the European Committee for Standardization (CEN) in cooperation with the International Standards Organization (ISO) and the European committee for Electrotechnical Standardization (CENELEC) in cooperation with the International Electrotechnical Commission (IEC) and can be used by manufacturers to prove their conformity [6].

2.3 Steps to safe machine design

In order to prove that their products conform to the Machinery Directive, machine designers must provide evidence of:

1. A thorough risk assessment based on ISO 141121 or EN 1050. The risk assessment looks at every possible scenario that could cause injury or death, disastrous impacts on the environment or destruction of production facilities. The mentioned standards aid designers in identifying hazards due to burning, electric shock, impact etc. and give designers insight as to the level of safety required.
2. The procedures used to reduce each of the risks discovered in step 1 such as:
    - Use of safe design principles (avoid pinch points; avoid the use of spoked wheels, correct cable thickness etc.)
    - Technical protective measures such as safeguarding, implementation of functional safety etc.
    - Preventative measures for residual risk such as warnings, staff training, etc.
3. Machine validation: manufacturers must show proof that their machine really meets its stipulated design criteria.

2.4 Modern functional safety standards

Many safety-related systems that would have previously used electro-mechanical or solid-state electronics now use programmable electronics instead. In the process and manufacturing sector, this commonly includes Programmable Logic Controllers (PLC's) and communication/ bus systems [3]. This has brought about a new set of challenges to functional safety systems because of potential failure due to program errors or untested combinations of coded instructions. This calls for up to date standards that are able to thoroughly evaluate every aspect of modern technology.

There are four main standards whose objectives are the determination of the level of safety required of both machinery and its

2.4.1 IEC 61508 & IEC 62061

IEC 61508 covers Electrical, Electronic and Programmable Electronic (E/E/EP) safety-related systems. This standard lays down the requirements for ensuring that systems are designed, implemented, operated and maintained to provide the required safety integrity level (SIL). The standard is made up of six parts that cover the following key elements [1]:

- Management of functional safety
- Technical safety requirements
- Documentation
- Competence of persons

Four SIL levels, SIL1-3 are defined, with SIL3 being the highest achievable safety level. The standard, relates the SIL with the probability of dangerous failure as shown in Table 1 below:

Safety Integrity Level (SIL)	Probability of a dangerous failure per hour (PFH_D)
1	$\geq 10^{-6} < 10^{-5}$
2	$\geq 10^{-7} < 10^{-6}$
3	$\geq 10^{-8} < 10^{-7}$

Table 1 - Relationship between Safety Integrity Level & PFHD

IEC 62061 is a 'lighter' standard that was developed from IEC 61508 and is of more relevance to the manufacturing industry where the resuts of failure are less catostrophic than those found in the process industry. Its application is limited to the electrically related safety control systems of machinery whereas IEC 61508 extends to cover all applications where safeguarding control systems are required. As with IEC 61508, IEC 62061 defines SIL 1-3 based on a scoring system that quantifies and adds together the frequency of exposure, the probability of avoidance, the possibility of avoidance and the severity of injusry.

2.4.2 EN954-1 & EN ISO13849-1

EN 954-1 deals with safety related parts (mechanical and electrical) of machinery and utilizes the results of the risk assessments to derive categories (i.e. CAT B, 1-4) of requirements for the safety.

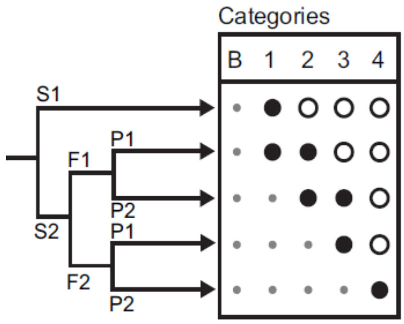

Figure 4 - Risk Graph from Annex B of EN 954-1

This standard has been replaced by ISO13849-1 which follows a similar procedure but uses a risk graph in to which the application factors of severity of injury, frequency of exposure and possibility of avoidance are input to determine the required performance level (PL_r) of a safety system. The standard goes on to show how the actual PL of a designed system can be verified by taking in to account: categories, failure rates, diagnostic coverage, common cause failures and systemic failures. It also relates PLs to SILs.

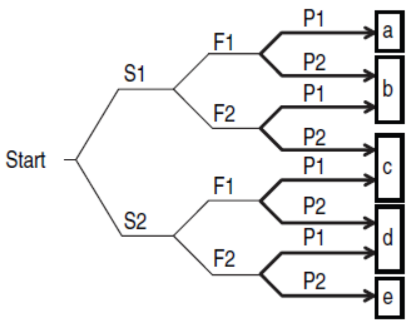

Figure 5: Risk Graph from Annex A of EN ISO 13849-1

Severity of the injury:	**Se**
• Irreversible injury:	Se2
• Reversible injury:	Se1
Frequency/ Exposure time	**Fr**
• Frequent up to continuous/ long:	Fr2
• Seldom up to quite often/ short:	Fr1
Possibility of avoidance	**P**
• Scarcely possible:	P2
• Possible:	P1

Table 2 - Severity of Injury

Because these standards are used interchangeably all around the world, most designers opt to describe the achievable safety levels of their machines or products in terms of the all three SIL, PL and CAT safety ratings.

2.5 Safety control systems

Functional safety systems will almost always include three fundamental sub systems as shown in Figure 6 [7].

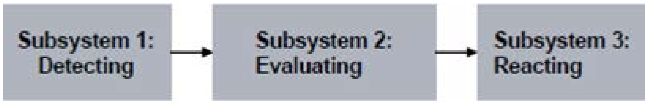

Figure 6 - Functional safety subsystems

Subsystem 1 is used for detection of safety related conditions for instance the opening of a safety gate. Sensors of all sorts (gate switches, proximity sensors, light curtains etc) would fall in to this category. Subsystem 2 includes devices capable of processing diagnostic and/ or error information. Devices in this category would typically include safety relays or safety PLC's. The bigger and more intesive an appliation is, the larger the processing requirements are on subsystem 2. Subsystem 3 refers to actuators of all sorts (e.g. contactors).

The combined safety system must be able to meet the safety requirements determined during the risk assessment process.

2.6 Safety Communication for Industrial Automation

Within industrial automation there is a trend away from central control structures to distributed local processing units. PROFIsafe is an IEC 61508-compliant integrated safety technology developed under PROFIBUS and PROFINET International and enjoys widespread international acceptance (4.1 Million nodes) within industrial automated systems [9]. It covers the entire communication path from the sensor over the controller to the actuator and integrates safety and standard communication on one cable. SICK, shown in Figure 6, is a manufacturer of safety laser scanners and has been applying the PROFISafe standard in hazardous area protection. See in Section 4.2 its application.

Figure 6 - Examples of safety laser scanners available from Sick [10]

2.7 Functional Safety Training

With reference to Figure 2, the UK HSE, through their studies, showed that control system failures due to operation and maintenance accounted for 15% of all failures investigated were, in part, due to inadequate training of staff. It was noted that despite differences in the underlying technology of the control systems used, the safety principles needed to prevent failure remained the same in each incident studied. Conclusively, the research carried out by HSE showed that operational and maintenance staff required not only knowledge of the control systems used but also of the governing safety principles. The biggest challenge faced with using the standards is that they can be difficult to interpret and implement without thorough training [8]. From an educational perspective, what seems to be lacking, despite the fact that functional safety has been around for a long time, is a well-balanced combination of functional safety theory and practice. Safety product trainers and promoters, for example, tend to focus more on the capability or functionality of their products and not so much on the underlying safety principles whereas educators in institutions tend to emphasise theoretical aspects over practical application.

3 EFFECTIVE METHOD FOR FUNCTIONAL SAFETY TRAINING

In order to provide effective al-round functional safety training, four universal training stations were designed and constructed for use within the Mechatronics Engineering curriculum as well as within short learning programmes offered at the Nelson Mandela Metropolitan University.

3.1 Safety stations

An image of one of the systems is shown in Figure 7. Each station makes use of a Siemens safety PLC (S7-315F-2PN/DP), an ET200s distributed IO unit with safety rated I/O and safety rated switchgear including two emergency stops, an assortment of push buttons and pannel lamps and two gate switches.

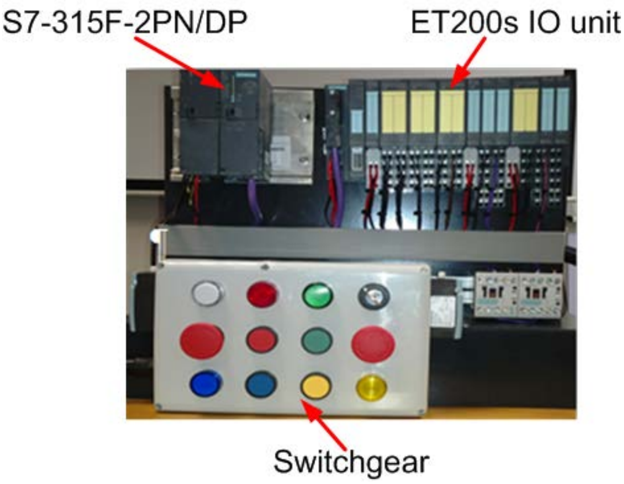

Figure 7 - Functional Safety Training station

The PLC is linked to the ET200s via Profibus and makes use of the Profisafe communication protocol to achieve safe communication.

The station was designed to meet the following general requiremens:

1. Ergornomic: Small, lightweight, easy to use and carry to off-site training locations.
2. Have sufficient IO to widely cover safety principles in order to effectively relate thory and practice.
3. Make use of safety rated sub-systems/ components.

3.2 A structured training approach

After a thorough review of the related safety standards, as well as an overview of safety wiring, programming techniques and fail-safe communication, the training takes on the following project-based, structured approach (by means of an actual application) in order to give learners a thorough understanding of concepts taught in the standards:

1. Each learner is assigned a task in the form of a machine that must be implemented safely. Examples of such tasks include presses, robots cells, welding fixtures and milling machines just to name a few.
2. The learner then performs a thorough risk assessment to identify all possible hazards associated with their machine. In so doing the required safety level is determined in terms of the required PL, SIL and safety category.
3. The learner then implements the safety system for their machine (using the simulator station and its available IO only) in order to reduce the risk to a tolerable level.
4. Finally the learner validates his/ her entire safety system to prove that it actually meets the required safety level. The validation process involves various calculations and looks at the safety level of the entire system including the sub components used such as Estops, gate switches, push buttons, key-switches, the channel wiring and the PLC program. The performance level achieved can be verified by looking at the following factors:
   a. The architecture of the safety related parts of the system (CATB, 1…4).
   b. The reliability of components including the mean time to dangerous failure ($MTTF_d$) as stipulated in the data sheets of the sub systems.
   c. The effectiveness of error detection or Diagnostic Coverage (DC).
   d. Common Cause of Failure (CCF).

e. PFHd – Probability of dangerous failure per hour.

The principles and techniques taught remain generic and not brand specific (such as Siemens in this case). This simply implies that the knowledge gained through this training can be broadly applied, independent of product brand.

4 CASE STUDY - FUNCTIONAL APPLICATION OF INTEGRATED SAFETY CONTROLLER FOR AUTOMATIC GUIDED VEHICLES (AGVS)

For world-class manufactures, automated materials handling is increasingly a competitive advantage and market differentiator. Since 2006 adapting a fleet of over one hundred Tugger motors into Automatic Guided Vehicles (AGVs) were part of a lean cost reduction initiative at Toyota Motor Manufacturing. For this world-class manufacturer, automated materials handling using AGVs have increased its competitive advantage and been a clear market differentiator [11]. The following describe the safety features and implementation of an industry safety standard controller for AGVs developed at the Advanced Mechatronics Technology Centre at the NMMU.

4.1 Safety features for AGVs

Safety features to ensure the safety of workers the AGVs and production equipment include [12]:

- Early warning collision detection

Sensors determine if an object is within a certain distance and then cause the AGV to slow down or stop if need be. The Sick S300 mini, discussed in Section 2.6, is an industry standard safety sensors was implemented.

- Contact sensors integrated into a bumper

Contact sensors detects if the AGV has hit something and can send a signal to turn it off. Bump sensors are sometimes used as a backup if the early warning collision sensors fail.

- E-Stop Buttons

Should something go wrong with the AGV, the E-Stop button can be pressed to shut off power to the AGV. The E-Stop is often hardwired and not software controlled to ensure that it will work even if the software is faulty.

- Visual and audion signals

AGVs can use warning lights and audio buzzers when in operation to alert workers to the presence of the AGVs.

Normally the safety systems have redundancy in them, such as E-Stops having two contacts not just one, as well as having more than one safety system

4.2 Integrated Safety Controller for AGVs

To ensure a high level of safety, three safety devices described used, namely: the E-stop, a bumper system and a Sick S300 Mini Remote. The control system for the AGV contains two subsystems. The first one is the PLC, which handles the normal operation of the AGV, including: Driving, navigation communication and light signals. The second system is a safety controller, which handles all the safety aspects of the AGV, schematic of components shown in Figure 8.

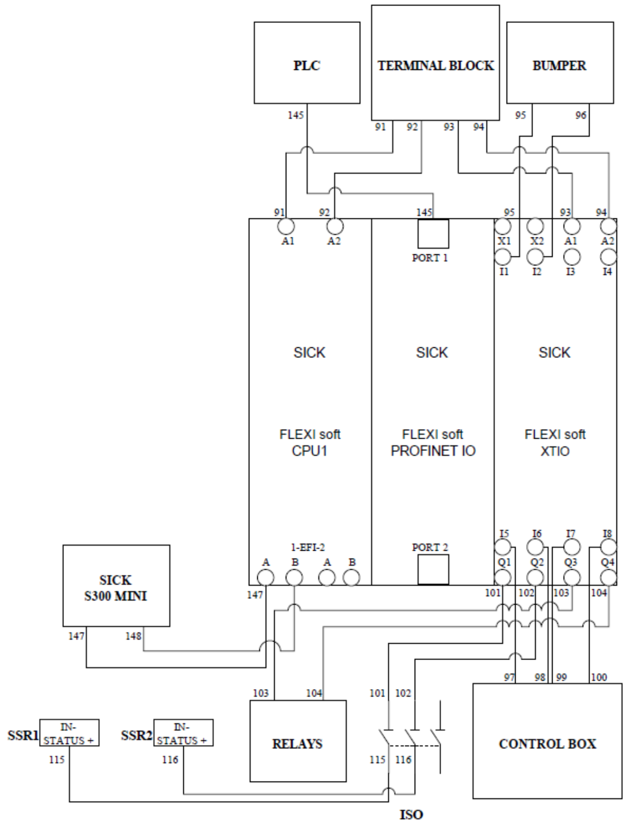

Figure 8 – Integrated Safety Controller for AGVs

There are two reasons for using the safety controller and not just the PLC. These are that the S300 uses a communication with built-in redundancy called Enhanced Function Interface (EFI) which the PLC does not support. The PLC is not safety rated, thus it cannot be used for safety functions, and it communicates to the safety controller using the PROFINET PROFISafe safety bus system.

5 CONCLUSIONS

Functional Safety is applicable to almost all areas of industry. This paper reviewed various aspects of Functional Safety in the machine design phase. Industry standard controllers are utilizing a modular and integrated safety approach. A safety integrated educational system to enhance teaching and learning into safety standards and programming was successfully introduced. Finally, a controller meeting the industry safety standard was implemented to show how various sensors can be integrated into an AGV system.

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STREAM C

Operations Management

Session C1: Production Planning and Scheduling

Session C2: Advances and Challenges in Logistics

Session C3: Modelling and Simulation

Session C4: Supply Chain Management

A Holonic Approach to Reactive Scheduling when Rush Orders Emerge

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Abstract
Rush orders can complicate the life of project managers when they emerge especially if they are of a high priority. Initially prepared process plans and schedules become invalid while extra capacity may be needed to meet the new demands placed on the shop-floor. However, with the era of distributed manufacturing, skills and resources can be shared in an optimal manner. The paper presents an application for automated management of resources in response to varying demands experienced by an industrial cluster of tool and dies workshops. A set of holons are utilized to monitor progress of orders in process while responding in real time to new demands placed on the system. The system utilizes the Petri-net protocol for the bidding function and automatically organizes the manufacturing function in a cost effective and timely manner. The ARENA discrete event simulation platform was utilized to demonstrate system's results in a virtual environment.

Keywords
Rush Order, Predictive schedule, Reactive schedule, Petri-net protocol, Holon, Holarchy

1 INTRODUCTION

Customers in the 21st century are increasingly becoming complex. Nowadays, it is the norm for businesses to experience ever changing requirements and needs from their unpredictable clients. Among these changes, a sudden increase in production demand due to rush orders is a main problem most manufacturers face. New orders can be introduced at any time with urgent due dates resulting in work-in-progress increase thus disrupting work flow within the production system.

Dewa et al. [1] identified rush orders as one job-related operational disturbance Tool, Die and Mould-making (TDM) firms in the South African Western Cape Province have suffered. When rush orders emerge, the previously prepared predictive schedule is rendered invalid and a new reactive schedule is required to maintain system performance.

In the paper, we suggest a holonic framework for reactive scheduling for scenarios where rush orders emerge. A case study based on a tool and die workshop in the Western Cape Province of South Africa is employed to demonstrate the approach. The structure of the paper is as follows: firstly, the impact of rush orders on the production shop-floor is discussed. Secondly we define the problem context using a case study before proposing a holonic model blue print for reactive scheduling. Finally we present the simulation study results of the proposed system.

2 LITERATURE REVIEW

2.1 The operational impact of rush orders

According to Wu and Chen [2], rush orders are immediate customer jobs that exceed the expectation of a currently operational Master Production Schedule (MPS). They may result from the arrival of new urgent orders, increase of volumes of pending orders or change of due dates of pending jobs to an earlier date. In a majority of production firms, the sales teams usually accept rush orders since they increase firm revenue and future clients. On the other hand, the production shop-floor rejects rush-orders due the strain they inflict on production planning, scheduling decisions and available resource capacity.

Integrating a rush order into an existing prepared predictive schedule can be challenging due to the impact they inflict on any production line. Researchers have identified numerous problems caused by rush orders.

2.1.1 Delay of Standarad Orders

Studies by Plossl [3] have revealed that there is a clear correlation between the acceptance of rush orders and the delay of scheduled standard orders. An increase in the number of rush orders accepted exponentially increases the time it takes to complete pending standard orders. Since rush orders are always prioritized, the throughput time of standard orders is extended as illustrated in Figure 1, a model developed by Trzyna et al. [4] to demonstrate the extent to which rush orders are delayed by standard orders.

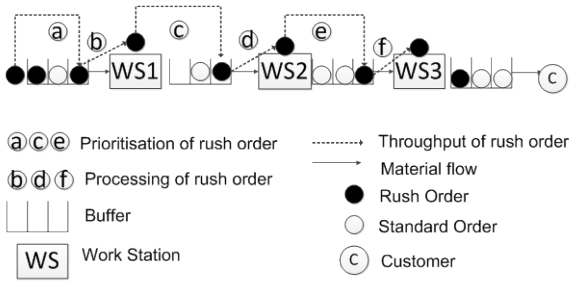

Figure 1 - Behaviour of rush orders (Trzyna et al., [4])

Wiendahl [5] added that the throughput time for any order results from the sum of order processing and interoperation times. The interoperation times for standard orders are significantly increased by the presence of rush orders.

2.1.2 Increase in inventory costs

Rush orders also impact significantly on Work-In-Process (WIP) levels. The more the rush orders the longer the lead times for standard orders and hence the higher the inventory holding costs.

2.1.3 Complexity in production planning and scheduling

The prepared shop-floor schedule with standard orders is rendered invalid when rush orders are added. Due to this challenge, rush orders need to be integrated into an existing plan in an optimal manner. A lot of research has been conducted on the decision of incorporating rush orders into an existing schedule. Studies by Wu and Chen [2] evaluated whether rush order revenue was worth it or not by taking into account the expenditure of tardiness costs invoked onto the standard orders. However, other researchers have considered the lateness factor only in making the decision.

2.2 Challenge of rush orders in tool-making firms

The South African TDM industry has been coined as a critical sector to the growth and sustainability of manufacturers in the nation. However, results of a recent benchmarking survey of the TDM sector (Malherbe, [6]) have revealed that most firms are struggling in the area of delivery lead times as compared to their global competitors [7]. Though the reasons for this trend are manifold, Mkhize [8] highlighted that in most of these firms, workflow is interrupted by the frequent occurrence of rush orders [8]. This trend has resulted in a significant compromise on delivery due dates.

However, due to intense global competition among tool-makers, the strategy of collaborative manufacturing is slowly gaining popularity in the Tool, Die and Mould-making sector. South African toolmakers have realized the need to focus on their core competencies and narrow their scope of value addition during the fulfilment of orders. As a result collaborative networks which share skills and resources are being formulated with the goal of expanding the resource capacity base. Eventually the firms position themselves to accept large orders. This makes the current manufacturing environment a distributed one.

2.2.1 Problem statement

Much research in the past has focused on how to deal with rush orders within a production shop-floor where the decision of accepting or rejecting a rush order is based only of the available capacity in a single workshop. Examples of such scholarly efforts include work by Chen [9] who formulated a heuristic model for justifying acceptance of rush orders. However, with the era of distributed manufacturing, the question remaining is: how best can rush orders be planned for in a distributed manufacturing environment? This paper attempts to answer the question through a framework designed using the South African tooling industry as a case study.

2.2.2 Holonic Control System for South African Tool Die and Mould-makers

Due to the unique reality of collaborative manufacturing and challenge of rush orders mentioned in the problem statement, novel applications or models are required by South African Tool makers. Holonic Control systems are a possible solution for handling shop-floor disturbances for firms operating in a distributed manufacturing environment [10].

Holons are a special type of autonomous agents which have the ability to make decisions and execute tasks on behalf of users. They are autonomous and cooperative building blocks of a manufacturing system capable of transforming, transporting and/or validating information or physical objects [11]. Holons are a special class of agents as illustrated in the work by Girret and Botti [12]. Their design and deployment assist in solving problems for cases where frequent disturbances are affecting operations. A holonic approach was used because the resulting architecture will be highly resilient to external and internal disturbances while it is adaptable to changes. When different holons interact to solve a problem, they formulate a holarchy.

Holons have been used to solve other production planning problems in manufacturing. Babiceanu et al. [13] used a holonic approach to solve material handling operations in a dynamic manufacturing environment. Akturk and Turkcan [14] applied a holonic approach to part-family and machine-cell family problems in a cellular manufacturing environment. The holarchy classes presented in the paper were specifically designed to handle rush orders during distributed production.

3 RESEARCH METHODOLOGY

Since Holons are a specific class of agents, frameworks for developing agents can be used to realise them. Hence, the Designing Agent-based

Control Systems (DACS) methodology proposed by Bussmann et al. [15] was selected as the appropriate methodology of building the system blue print. The steps taken in this methodology are illustrated in Figure 2.

Specification of the production system problem context is the main input of this methodology. A case study of five tool rooms forming a collaborative cluster in the Western Cape Province of South Africa was utilized. The data concerning these firms was derived from field visits and facility tours.

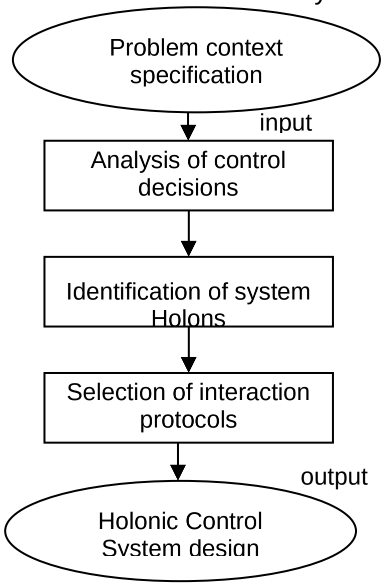

Figure 2 - Steps in DACS methodology [13]

The five firms were randomly selected based on their collaboration in producing parts for the automotive industry. The purpose of the field studies was to observe the system resources within the firms and investigate the frequency of occurrence of rush orders during weekly production. All firms agreed to take part in the study and as such they were visited during different time periods. The expert opinion method was used to select the appropriate respondents who in this case were shop-floor operations managers in their firms. The variables in the observation schedule questionnaire were:

- Main products and process flow methods
- The frequency of rush orders in the firms
- Predictive scheduling heuristic rule employed
- Reactive scheduling heuristic rule employed

The purpose of this analysis was for understanding of the problem context. A facility tour was also conducted in each of the firms. For the purposes of this study, only a single main product was selected. Secondly, a simulation study was conducted for one of the observed firms. A simple job-shop manufacturing firm which produces sintered car sensor rings was selected for this purpose. The purpose of the simulation study was for evaluation of different decision strategies the developed holarchy suggests in response to rush orders so as to minimize delays in standard orders. Discrete event simulation is an essential tool for testing different scheduling strategies without affecting the real-world system [16]. Arena 14.0 discrete event simulation package (research version) was employed for this purpose. The information derived to define the problem context was employed for analysis of the control decisions, identification of the required holons and selection of the appropriate interaction protocols.

3.1 Case study: Problem context

The selected case study is a tool room using semi-automated production flow-line. The firm produces powder metallurgy parts for cars such as sensor rings, flanges, lock components and pump components. The case study will focus on different orders (both standard and rush) of the main product identified which is the sensor ring. When a rush order is introduced to the system, it is added to the beginning of the queue. The process flow diagram for the sensor ring fabrication process is shown in Figure 3 while the order data used in the simulation study is shown in Table 1.

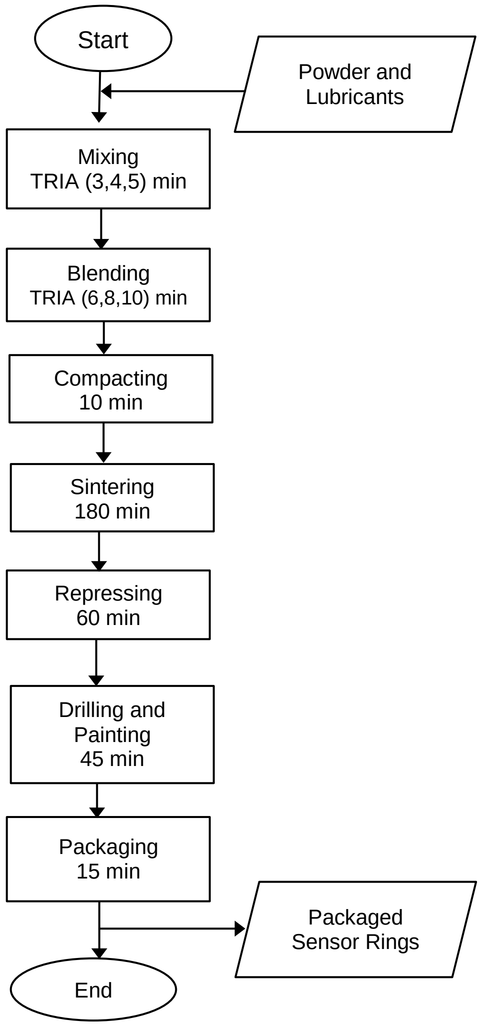

Figure 3 - Process flow diagram

3.2 Facility Layout Diagram

The manufacturing facility for the tool work shop under study is a small facility with 10 operators and 11 system resources. The facility layout is illustrated in Figure 4 while the system components for the facility are given in Table 2. A mapping of processes and components required at each stage are clearly given in Table 3.

According to the manufacturing facility's perspective (derived from the field studies), the total throughput time of standard orders is too high whenever there are rush orders introduced. This delay renders the facility uncompetitive when it comes to delivery due dates. Hence, lead time reduction for both standard and rush orders is crucial to enhance the productivity and the competitiveness of the plant.

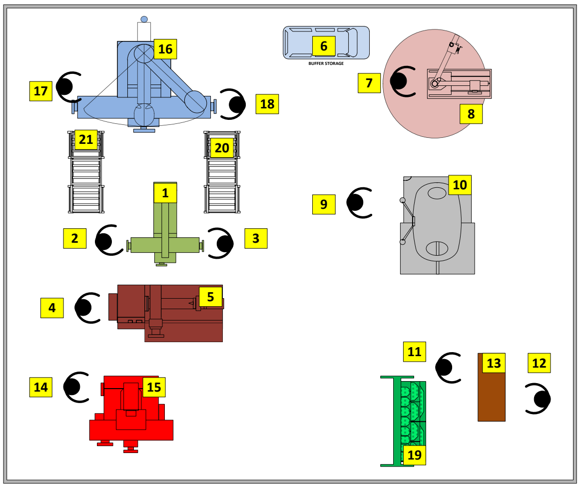

Figure 4 - Manufacturing facility diagram

The resources shown in the facility are arranged following a job-shop set up which is being used to fabricate different parts. However, the orders presented in Table 1 are the ones utilized to illustrate the functioning of the designed framework.

4 RESULTS OBTAINED

4.1 Holonic framework developed

Using the production problem described in Section 3.1, the Holonic model blue print for dealing with rush orders was developed using the Java Agent Development Framework (JADE). The main objective of the system is to minimize tardiness costs associated with the lateness of standard orders due to rush orders by searching and allocating more resources from within a cluster's available capacity.

4.1.1 Analysis of control decisions

To minimize the effect imposed by rush orders, the key decisions the system should be capable of making are:

- Order definition (standard or rush)
- Process flow mapping
- Resource searching
- Resource availability assesment
- Resource allocation

The control parameters for the decisions include throughput time and tardiness costs.

4.1.2 Holon definition

The identified control decisions were utilized to define the required holons for the system. The identified holons include:

- ✓ Order Holon (OH)
- ✓ Resource Holon (RH)
- ✓ Supervisor Holon (SH)

Every incoming order results in the creation of an Order Holon (OH). The Order Holon carries order data concerning due dates and process flows. Order Holons have to compete for Resource Holons (RHs). The Resource Holons carry information concerning the available operational resources required to do tasks. Information on capability and availability are made available in the RHs. The Supervisor Holon has a bird's eye view of the entire system is responsible for close monitoring of the progress of all Order Holons. The hierachial structure of the holons is represented in Figure 5.

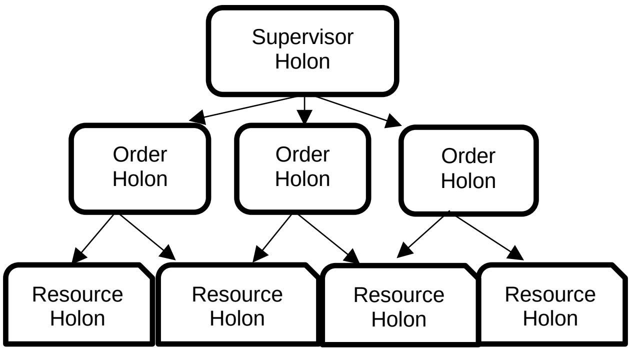

Figure 5 - Holarchy diagram

4.1.3 Interaction protocols

Order Holons have to compete and bid for resources during the searching process. The appropriate protocol selected to achieve this goal in the holarchy was the Petri-Net Protocol. The Resources advertise their availability and costs within a virtual environment and the Supervisor Holon makes the final decision on which resources are selected for the job based on minimizing the tardiness costs.

4.2 Simulation study

4.2.1 Model Logic

The simulation model for the tool room under study was fully developed using the ARENA 14.0 research version. The shop-floor manager approved the model behaviour during the verification process and using historical input data of previous orders, the model was validated. For demonstrating the decision making of the holarchy described in Section 4.1.3, resource data on the tool rooms visited were stored on an Excel spread sheet which was linked to the simulation model and a Java Agent Development Platform with the holons.

Upon entry of a rush order, the Order Holons bid for Resource Holons available. The Supervisor Holon finally reallocates and develops a reactive schedule with the minimum tardiness costs and low impact on throughput of standard orders.

4.2.2 Model Results

The results for the simulation study are summarized in Table 4. The Job lateness was significantly reduced when using the Holonic Approach resulting in a 65% tardiness cost reduction.

5 CONCLUSION

5.1 Discussion

Organizations within collaborative networks can take advantage of the resources and skills available to them within a network to facilitate handling of orders. To facilitate resource allocation during manufacturing in a distributed environment, holons can be designed and developed for global decision making. The flow diagram in Figure 6 illustrates the proposed approach to reactive scheduling using the paradigm of holons.

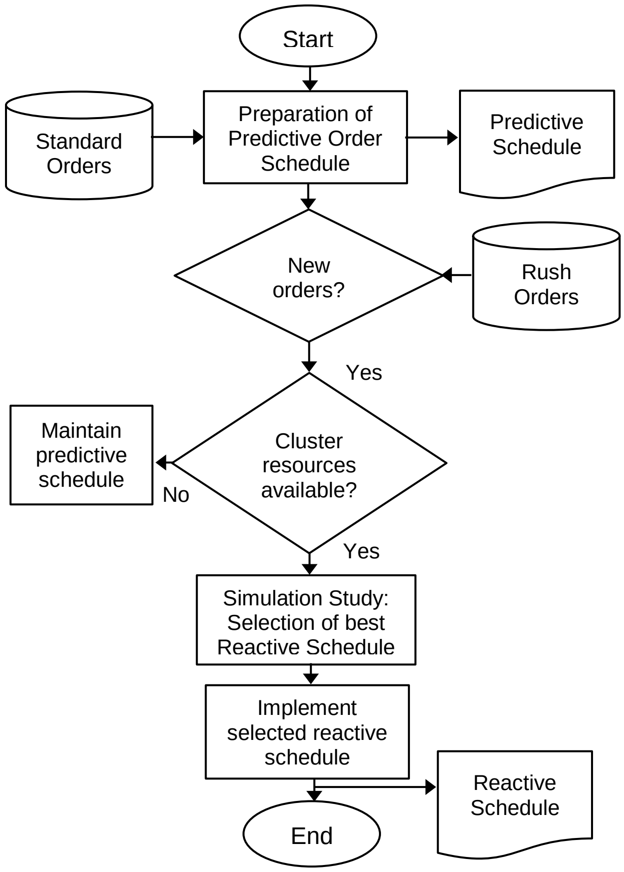

Figure 6 - Proposed reactive scheduling approach

The designed framework serves as a decision support system for real-time scheduling when interruptions due to rush orders emerge. The required capacity can be found and allocated in response to the sudden demand increase hence significantly minimizing waiting time.

5.2 Future work

The study was on design of a holonic blue-print for reactive scheduling when rush orders emerge with the goal of minimizing tardiness costs. Future work can be done on developing other holonic systems to handle other disturbances like machine breakdowns in a real-world firm environment.

6 ACKNOWLEDGEMENTS

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8 BIOGRAPHY

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Stephen Matope is a Senior Lecturer in the Department of Industrial Engineering at Stellenbosch University. He has published several journal and conference papers on manufacturing related topics. His research interests are in manufacturing. He holds a Ph.D. in engineering obtained at Stellenbosch University.

Order Number	Volume required	Order Type	Due Date
001	5	Standard	14 days
002	7	Rush	3 days
003	6	Rush	5 days
004	3	Standard	20 days
005	9	Rush	7 days

Table 1 - Standard and Rush Order Data

Number	Name of Resource
1	Mixing and compacting machine
2	Operator 1
3	Operator 2
4	Operator 3
5	Milling centre
6	Buffer storage space
7	Operator 4
8	CNC Machine
9	Operator 5
10	Drill press
11	Operator 6
12	Operator 7
13	Workbench
14	Operator 8
15	Lathe machine
16	Blending Machine
17	Operator 9
18	Operator 10
19	Delivery rack
20	Push rack 1
21	Push rack 2

Table 2 - Manufacturing facility system components

Process	Components
Mixing	Mixing and compacting machine, Operator 1 and Operator 2
Blending	Blending machine, Operator 9 and Operator 10
Compacting	Operator 3 and Mill Press
Sintering	Operator 4 and CNC machine
Repressing	Lathe Machine and Operator 8
Drilling	Drill Press and Operator 5
Painting	Operator 6, Operator 7 and Workbench
Packaging	Operator 6, Operator 7 and Workbench

Table 3 - Process-system data relationship

Order Number	**Order Type**	**Completion Date**		**Lateness/Tardiness**		**Tardiness Cost (R20/day)**	
		Normal	**Holonic**	**Normal**	**Holonic**	**Normal (Rands)**	**Holonic (Rands)**
001	Standard	15 days	14.2 days	1 day	0.8 days	20	16
002	Rush	16 days	7 days	13 days	4 days	260	80
003	Rush	18 days	9 days	13 days	4 days	260	80
004	Standard	24 days	15 days	4 days	0 days	80	0
005	Rush	32 days	18 days	25 days	11 days	500	220
Total Tardiness Costs						**1120**	**396**

Table 4 - Summary of Simulation study results

System for Production Planning of Reconfigurable Manufacturing Systems

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Abstract

Manufacturing companies are affected by challenging dynamics due to shortening product and technology life cycles as well as increasing numbers of variants. As a consequence, manufacturing companies have to adapt their manufacturing systems in frequent and short intervals to secure their competitiveness. One approach to ensure companies' success is the concept of reconfigurable manufacturing systems (RMS). While production planning becomes increasingly complex in this context, it has to be reliable and quick at the same time. Thus, a novel system for production planning of reconfigurable manufacturing systems realizing the integration of RMS' key characteristics in production planning, enables companies to effectively adapt to changing market conditions. The planning system outlined in this paper consists of a data model, a configuration management and a method for production planning. The focus of this paper is the configuration management as well as the approach for machine-scheduling.

Keywords

Reconfigurable Manufacturing System (RMS), Production planning and control (PPC), Machine Scheduling

1 INTRODUCTION

The environment of manufacturing companies is due to reductions in product and technology cycles [1; 2] and the increasing demand for individual products described as highly dynamic [3]. For their competitiveness it is therefore essential to quickly adapt to changing market conditions [4]. One approach to ensure companies' ability to act successfully in this environment is changeability. Changeable systems can be distinguished by the fact that they are able to react with their inherent flexibility, but can also respond to unpredictable situations [1]. In production, major approaches for increasing changeability are reconfigurable manufacturing systems (RMS) [5]. As a consequence, reconfigurations in manufacturing systems raise the complexity of planning and scheduling processes [6]. With regard to the area of production planning and control (PPC) a more sophisticated planning is needed [7]. For an efficient planning and control of production processes RMS' key characteristics have to be considered continuously. From today's perspective appropriate PPC systems cannot deal with these characteristics [7]. Production-side changes, e.g. adapting the machine configuration by changing the spindles, are usually not adopted in planning systems. Furthermore, the provided production flexibility is not established in production planning and control. To meet these challenges, a novel system for production planning of reconfigurable manufacturing systems with reliable planning data and adopted methods is required.

2 RECONFIGURABLE MANUFACTURING SYSTEMS

In the following chapter RMS' key characteristics, differentiations to dedicated manufacturing lines (DML) as well as flexible manufacturing systems (FMS) are outlined. Finally, requirements for a system for production planning of RMS are stated.

2.1 Classification and differentiation

While the concept of reconfigurable manufacturing systems has gained importance since 1999 by Koren et al. [5], dedicated manufacturing lines and flexible manufacturing systems are already widespread in industry [8]. The significant differences between DML, FMS and RMS are the systems' flexibility and scalability concerning capacity and product functionality (see Figure 1).

In the past, production technology has been dominated by dedicated manufacturing lines and product-specific processing facilities [1]. Dedicated manufacturing lines are designed for a specific product or product range and a high throughput. With a high degree of utilization of production capacity, low costs can be achieved [8]. However, the capacity of a DML is fixed and cannot be adapted according to the current demand situation. If the demand within the life cycle goes back, e.g. at the beginning and at the end of a product life cycle, inefficient overcapacities occur.

Starting from fluctuations and turbulence, flexible manufacturing systems have been developed. These systems are built up with all possible set-ups concerning flexibility and functionality [4]. Adaptions can only be carried out within their a priori pre-determined flexibility with different flexibilities (e.g. product flexibility). Thus, only a pre-defined product spectrum and production amount within their flexibility corridor can be produced [8]. To summarize, FMS are limited in capacity as well as in functionality [5]. Adaptions, which go beyond this flexibility, require substantial efforts and are linked with high capital investments [5; 8].

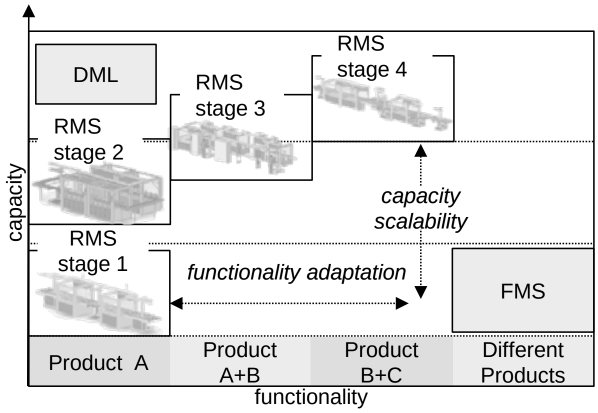

Figure 1 - Comparison of DML, FMS and RMS [according to 5]

With the aim to combine the advantages of DML (e.g. low production costs) and FMS, the concept of reconfigurable manufacturing systems emerged. RMS can be described as dynamic systems that can deal with unpredictable situations [5]. Reconfigurability is defined as the ability to customize the behaviour of a system by changing its configuration [9]. Key factors of RMS are the rapid adaptability of functionality and the scalability of capacity to the market conditions [4; 5]. These changes are implemented with minimal efforts in time and costs [1; 5]. Further, RMS are specified by the key characteristics modularity, integrability, customization, convertibility and diagnoseability. In contrast to reconfigurability convertibility requires (e.g. setting of tools) less expense for the preparation of the working system [10]. To meet market requirements, RMS provide on demand customized flexibility through capacity scalability and incrementally different functionalities [4; 8]. In contrast, DML are fixed in their capacity and FMS feature a general a priori-fixed flexibility. Furthermore, FMS can produce multiple products at installation time, whereas RMS are designed for a certain product portfolio (e.g. product A at the beginning and B+C in the extension stage four).

2.2 State of the art for production planning

The potentials of RMS have been highlighted by several authors in the past. The recent research activities in the field of production planning and control can be divided into the themes generation and selection of configurations [11-14], capacity planning [7; 15-17] and machine scheduling [18-20].

Configurations are regarded as essential planning elements for RMS. One focus of the research activities is the generation and selection of these configurations. The majority of the research is focused on the selection of the optimal configuration based on decision criteria. Koren and Shpitalni [12] develop system configurations by calculation the number of required machines and stations. Shabaka and ElMaraghy [13] generate configurations by comparison of the component requirements and the available resources. The performance of machine layouts on productivity is described by Youssef and ElMaraghy [14].

In the field of capacity planning several publications deal in general terms with the scalability of RMS by adding or removing equipment. Bruccoleri et al. [7] show an agent-based model for the coordination of capacity for multinational companies. Deif and ElMaraghy [15] determine the need for capacity and functionality of the production system from the market demand. In addition the selection of configurations with the goal of optimal scaling of capacity is examined in [16]. Toonen et al. [17] point out opportunities for capacity control and adjustment by means of reconfigurable machine tools.

The effect of determining the scope of part families to the machine scheduling examined Galán [18]. The size of a family is chosen so that reconfiguration costs, overcapacity and over-functionalities are minimized. Nehzati et al. [19] propose a fuzzy logic-based scheduling model for RMS. Bensmaine et al. [20] provide an integrated process and machine scheduling for RMS.

The state of the research illustrates that no continuous approach for production planning of reconfigurable manufacturing systems is available. Furthermore, a number of methods exist that cover parts of specific areas of production planning and control. The selected approaches are predominantly isolated applications and their integration in procedures of production planning is unclear.

2.3 Requirements for production planning

To ensure efficient planning processes for RMS, the key characteristics have to be integrated continuously into the PPC. In particular, system and resource configurations have to be described in customizable, configuration-dependent planning data. Further, the general performance, the feasible production operations and technologies (e.g. milling) as well as the geometrical characteristics (e.g. available space) of manufacturing resources are to be transferred to resources' configurations. Besides, the possibility to assign configurations to production resources has to be provided. For an automatic allocation of production operations to configurations decision criteria for the configuration selection must be defined. In addition to technological capabilities, configurations distinguish by their efficiency. With the help of a performance-evaluation of configurations (e.g. with KPIs), a selection-approach is to be supported. To enable production planning for RMS, reconfigurations have to be modelled (e.g. with the help of petri-nets). Basis for reliable planning results are feasible input data. Therefore, work and process plans have to be extended to the possibility of configurations. For the elevation associated with the customized planning data, new planning methods with the capability to deal with scalable capacities and changeable functionalities need to be developed.

3 SYSTEM FOR PRODUCTION PLANNING OF RECONFIGURABLE MANUFACTURING SYSTEMS

3.1 System overview

The significance of the characteristics of RMS as well as the quality of planning data are the main enablers to cope with todays' constantly changing requirements. Due to these challenges, the goal of this publication is the development of a system for production planning of RMS (see Figure 2). The planning system is based on the approach described in [21].

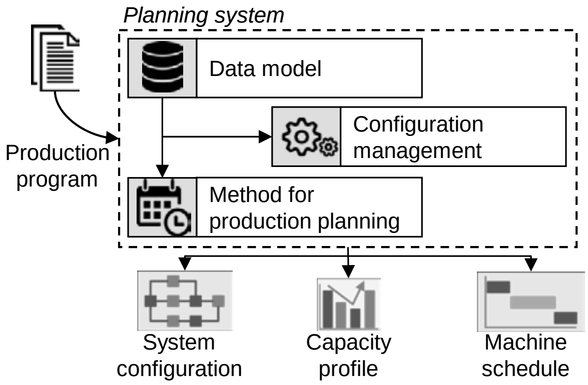

Figure 2 - System for production planning of reconfigurable manufacturing systems

As a prerequisite for the production planning the generic *data model* represents configuration-based capabilities of manufacturing resources. Based on the data models, the *configuration management* is to model, assign, adapt and monitor resources' configurations. Finally, a sequential *method for production planning,* consisting of approaches for system planning, capacity planning and machine scheduling, enables the utilization of the key characteristics in planning processes.

3.2 Data model

As the resources' technical and planning capabilities depend on the current configuration, a data model has been developed and is described in [22]. The model consists of the classes *resource, configurations, modules* and *manufacturing process*. In the class *resource*, all static properties are summarized. The class *configuration* is used to display configuration-dependent capabilities. In order to compare the configurations in terms of performance, indicators based on VDMA 66412-1 of the operating data (e.g. throughput), are integrated. In the class *module*, the changeable modules (e.g. spindle) are described. The class *manufacturing processes* describes the technological capabilities

3.3 Configuration management

The main goals of the configuration management are the assignment of suitable resource configurations for each production order and the modelling of configurations as well as possible reconfigurations. The functions of the configuration management are described in the following sections.

The *configuration modelling* of systems and resources with their capabilities and states is realized with the help of a petri-net approach. An example is illustrated in Figure 3. Based on resource configurations ($RC_{n.i/j}$) a configuration net is generated. Each reconfiguration can be described by the reconfiguration vectors ($\mathbf{r}_{ij}$) and the changes in the capabilities are shown in the data-set of the state (e.g. increasing throughput by reconfiguration from $RC_{1.3}$ to $RC_{1.2}$). The actual state of the resource is displayed in the state-vector ($\mathbf{s}$).

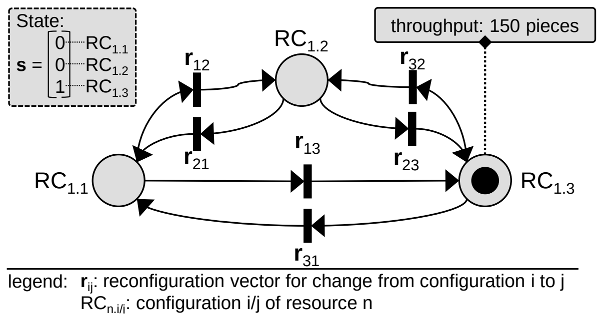

Figure 3 - Configuration modelling with petri-net

A central component of the configuration management is the *configuration assignment*. A technological and capacitive matching between operations requirements and the resources capabilities takes place.

Based on the criteria cost, time or technology appropriate configurations for production operations are identified. With the help of the classification system, providing a general description of production operations for production planning, a technological assignment can be executed. For this purpose, a numbering system containing information about the manufacturing processes (MP_i) and the geometry of the components is used (see Figure 4). The numbers one to four help to identify the production steps and represent the manufacturing process in accordance with DIN 8580 [23]. The subcategories of each main group are characterized by given standards. In addition to the manufacturing processes information, data about the work piece shape and the roughness are integrated in the numbers five and six to derive required tools and the necessary working space of the machine. Thus, machine and tool parameters can be determined. With the presented classification system a technology matching can be conducted on system and resource level (see Figure 5). Therefore, the operations requirements (MP_{OI-IV}) and the possible manufacturing capabilities (MP_{RI-IV}) are each summarized in a technology vector and compared.

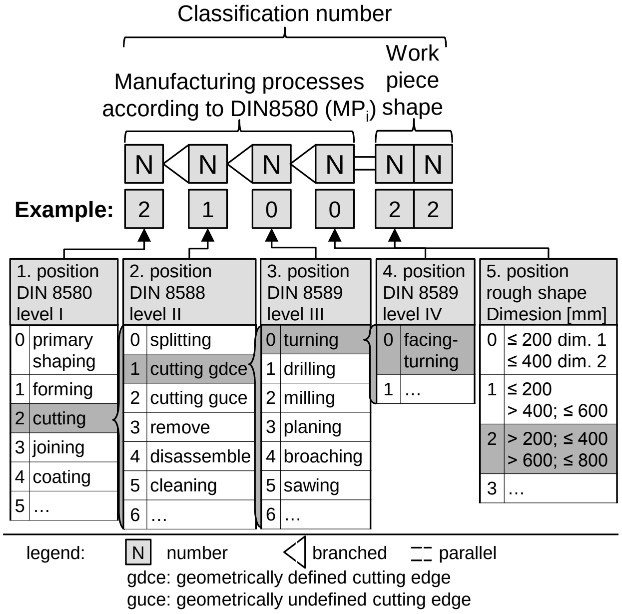

Figure 4 - Classification system for the description of production operations

If changes in the production program (e.g. new product features) emerge, reconfigurations are identified. In connection with the reconfiguration, the *configuration adaption* customizes or generates new configurations (e.g. capacity scaling by adding new machines). Moreover, the *configuration monitoring* checks permissible functional areas, documents the progress and indicates the status of the configuration management.

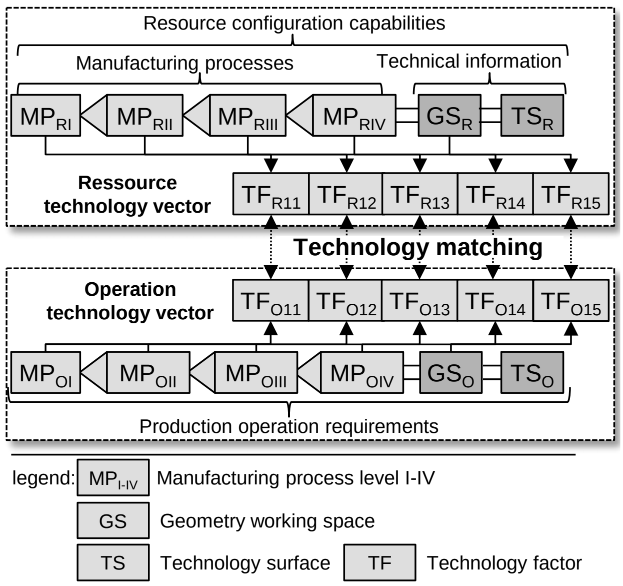

Figure 5 - Technology matching between resource capabilities and operations requirements

3.4 Method for production planning

The method for production planning is divided into the phases *system planning, capacity planning* and *machine-scheduling*. The focus within this section is the machine-scheduling approach.

The *system planning* is to generate and select different system configurations. As decision-making criteria the fulfillment of the capacity requirements and an adapted evaluation of reconfiguration smoothness based on [24] are used. From the basis of configuration-depended busy and reconfiguration times, the *capacity planning* calculates capacity profiles for all possible combinations.

The developed algorithm in the context of *machine-scheduling* for reconfigurable manufacturing systems is illustrated in Figure 6 and divided into two parts.

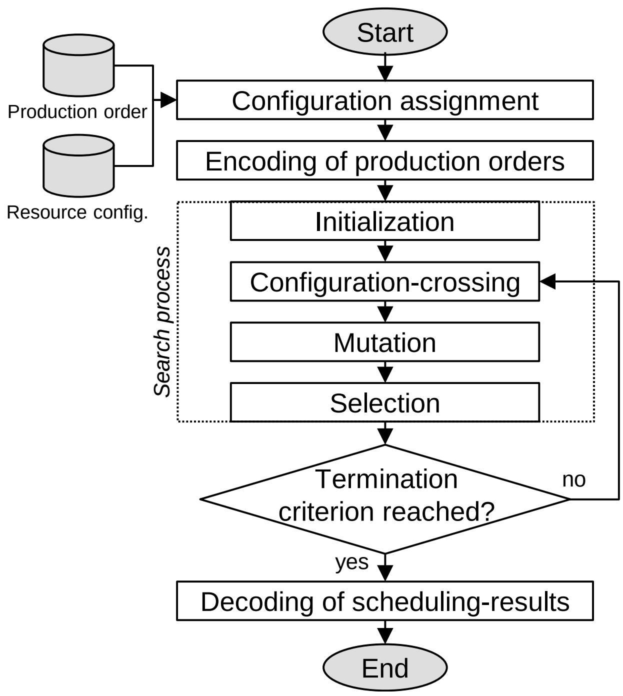

Figure 6 - Machine-scheduling algorithm

In the first part, the configuration assignment identifies the resources that have the capabilities to perform the operations within the production orders and possible resource configurations are assigned. In the second part a cost minimal resources' configuration for each operation of the production orders is searched. In the following, the crucial steps of the reconfiguration-oriented scheduling are elucidated.

At the beginning of the algorithm, the configuration assignment (see section 3.3) identifies possible configurations for the production operations and integrates them in the work plan. The second step is the transfer of the production orders into a form for the search process. Since there are different alternatives available for configuring each operation, consequently multiple solutions are generated. An example for the encoding is shown in Figure 7.

To speed up the search process, a genetic algorithm is used. The procedure of the algorithm includes the initialization, the configuration-crossing, the mutation and the selection. The goal of the initialization is to generate initial solutions serving as the first generation of the genetic algorithm. The generation of the initial population is done randomly. With a one point crossover operator the numbers are crossed. By crossing and mutation, new children are generated. Finally, all solutions within the population are compared concerning their fitness.

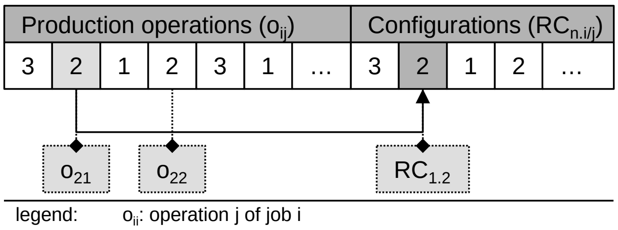

Figure 7 - Example for encoding production operations and resource configurations

The reconfiguration-costs as well as the occupancy-costs for the entire production plan are used as the fitness value (f) in the selection step (see equation (1)).

$$f = C_{total} = C_{reconfiguration} + C_{occupancy} \qquad (1)$$

For the calculation of the reconfiguration costs ($C_{reconfiguration}$) the reconfiguration smoothness (RS) of Youssef and ElMaraghy [24] was adapted to the resource level (RS_R). For the reconfigurations-costs a matrix based on the RS_R values, the number of changes of $RC_{n.i}$ to $RC_{n.j}$ as well as a system specific cost factor for each change are used. The occupancy costs ($C_{occupancy}$) consist of the configuration-dependent busy times and the machine hour rates. The algorithm ends when the termination criterion is reached.

4 PROTOTYPICAL IMPLEMENTATION

The described method for production planning is set up in a software prototype consisting of a scheduling system, a simulation model for the capacity planning and the respective data bases (see Figure 8). Manufacturing resources and production orders can be loaded into the system through xml-descriptions.

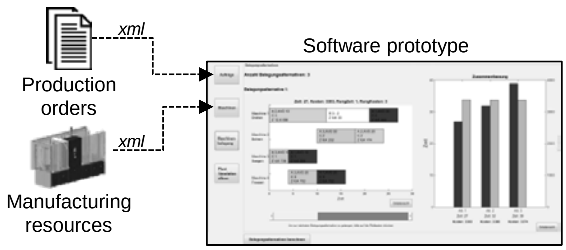

Figure 8 - Elements of the software prototype

The simulation model consists of four workshops with up to five reconfigurable production resources each. Both the system and the resources have different configurations and can be reconfigured. First findings indicate that the method for capacity planning affects the machine utilization. Further, the configuration selection through the machine-scheduling approach is realized. In the context of the realization of a prototypical implementation in a realistic production environment as well as a simulation-based validation, the general applicability needs to be demonstrated based on an industrial application scenario.

5 CONCLUSION

Manufacturing companies need to adapt their production concepts repeatedly to changing market conditions. One approach to ensure companies' success are reconfigurable manufacturing systems. To support the features of these systems, appropriate planning approaches are necessary. In the context of this publication a system for production planning of RMS with focus on the configuration management and the scheduling approach has been demonstrated. The software prototype provides a flexible basis and will serve as basis for a forthcoming simulation-based validation.

6 ACKNOWLEDGMENTS

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Agent based Job Scheduling for a Vehicle Engine Reconditioning Machine Shop

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Abstract

Job scheduling at a machine shop is a multi-decision criteria problem whose skills are acquired after some years of experience. For Small, Medium to Micro Enterprises (SMMEs) with limited machinery the objective when scheduling jobs should not only focus on machine utilization but also on the increase of job through put. The paper presents an agent based job scheduling system for a vehicle engine reconditioning machine shop to assist decision makers in job scheduling. The Analytic Hierarchy Process (AHP) method was used to compute the relative weights of each decision criteria used for job scheduling considering the job priority. The value of the job, the number of operations to be performed, the engine type, the frequency of the customer and the company to customer relationship rating are used to prioritize the jobs. A Multi Agent System (MAS) comprising of the provider, job allocator and machine agents is developed using the Java Agent development framework (JADE) methodology and modelled using Unified Modelling Language (UML 2). The provider agent schedules all the jobs based on job weight and earliest due dates. The job allocator agent is responsible for making sure that all the scheduled jobs are allocated to all the machines after which they are registered as complete jobs and can leave the system.

Keywords

Multi Agent System, Analytic Hierarchy Process, JADE

1 INTRODUCTION

The increasing advancements in technology have resulted in an increase of complexity in the product designs. This places a huge impact on the machinery, equipment, tooling as well as skills needed for their repair and maintenance. Several machine shops in the Small, Medium to Micro Enterprises (SMMEs) category employ traditional methods of scheduling jobs as well as monitoring of their systems. Modern day technology has necessitated the need for more reliable, flexible and cheaper approaches during conduction of operations within a company in order to fully realize the associated profits.

A typical vehicle engine servicing machine shop has several machines used to perform different types of operations during the reconditioning of the vehicle engine and its components. Scheduling of jobs on the machines is a multi-decision criteria which can take up a significant amount of productive time if not properly planned. In one instance, jobs may be scheduled using First In First Out (FIFO), while in other cases due dates or price especially when the company wants to generate quick income. The frequency with which the customers bring in jobs is often used in certain instances but there is no standard logic to which these assignments are based. Decision makers often consider factors to do with the engine type, existing relationship between the customer and the company and the number of operations to be performed in coming up with the best schedule to execute the jobs. This paper seeks to design a job scheduling system that will minimize lead times, increase due date reliability and customer satisfaction as well as ensuring profitability to the company.

2 RELATED LITERATURE

A manufacturing scheduling problem is one of the most difficult of all scheduling problems in that it is almost impossible to find an optimal solution without the use of an enumerative algorithm, with computation time increasing exponentially with problem size. Bagchi [1] and French [2] have given a more detailed discussion on the scheduling problem. Various methods which include heuristics, constraint propagation techniques, constraint satisfaction problem formalisms, Tabu search, simulated annealing, GAs, neural networks, fuzzy logic have been suggested in finding the solution of the scheduling problem as discussed by Zweben and Fox [3].

Traditional scheduling methods i.e. analytical, heuristic, or met heuristic use simplified theoretical models and are centralized as all computations are carried out in a central computing unit. This makes them to face difficulties when they are applied in the real world [4]. To take care of the short comings of traditional methods, intelligent agent technologies which are innovative and have a distributed approach which is more flexible, efficient, and adaptable to real-world dynamic manufacturing environments can be implemented. Some of the advantages agent based approaches for distributed manufacturing scheduling are discussed by Shen [5].

2.1 Agent based manufacturing scheduling

Autonomous agents have been used in short term production planning by Lin and Soldberg [6]. The shop floor is modelled as a market place where agents negotiate on the basis of a fictitious currency using contract net protocol. Macchiaroli and Riemma [7] added an iterative auction process to the negotiation process to enable parts and resources to adjust price taking into consideration the resource contention. The model results show that the agent approach has a better performance to dispatching rules like SPT, EDD, MST and CR.

Shaw [8] also used the contract-net method in developing a dynamic scheduling system for cellular manufacturing systems. Once a cell completes a job it broadcasts the task announcement to the other cells which checks if they have the required resources and submit the estimation of the earliest finishing time (EFT) or shortest processing time (SPT) to the job. The cells then negotiate to determine the route of the job. Shaw's experimental results indicated that the bidding scheme with EFT (earliest finishing time) outperformed the bidding scheme with SPT (shortest processing time).

Oulhadj et al. [9] presented a negotiation strategy similar to the Shaw's [8] approach. They added a resource agent responsible for establishing the negotiation with other resource agents in order to select the most appropriate resources to allocate to the specific task operations. The contract-net protocol was extended to a multi-contract net protocol allowing it to schedule several tasks simultaneously. Their experimental results showed that the time required to schedule operations with this approach and the run time including scheduling and execution both are linear rather than exponential with the increase of the number of scheduled tasks.

Dewan and Joshi [10], [11] developed an auction-based scheduling mechanism for a job shop environment where Lagrangian relaxation is used to decompose the problem and currency is used as the means for agent negotiation.. Whenever a machine has free time slots the machine agent announces an auction for time slots. Job agents then bid for the time slots by submitting the cost that they are willing to pay. The goal of the job agent is to minimize cost, while the machine agent tries to maximize the cost of the time slot. After the auction is complete the machine agent will then determine the best bid for the earliest time slot of the next operation.

Siwamogsatham and Saygin [12] used a model developed by Macchiaroli and Riemma [7] to develop an auction based algorithm for real-time scheduling of flexible manufacturing systems with alternate routings. They modified the cost function of Macchiaroli and Riemma [7] to incorporate time as the primary criterion. The model was compared with various priority rules on the basis of average tardiness, average lateness, average due date deviation, utilization balance, average throughput, average wait time and total cost, using simulation. The results show that auction based approach outperformed the priority rules on most performance measures.

In this paper an agent based job scheduling system developed uses the Analytic Hierarchy Process (AHP) to compute the relative contribution of each criteria used by the case study company and hence determine their corresponding weight for each job. AHP is used to solve multiple criteria decision making problems. Data is decomposed into a hierarchy of alternatives and criteria after which the information is synthesized to determine relative ranking of alternatives. Comparisons of the analytic hierarchy process contains both qualitative and quantitative information using informed judgments to derive weights and priorities. According to Saaty [13] the analytic hierarchy process is one of the most effective tools for dealing with complex decision making. This may help the decision maker to set priorities and make the best decision. In the system developed weights found from AHP are jointly used with Earliest Due Dates (EDD) and Shortest Processing Times (SPT) to create a job schedule with which the jobs are to be processed. The primary ordering is done on each job weighting after which the earliest due dates are used to order between the jobs of the similar weighting.

3 METHODOLOGY

Interviews with the company middle and top management were used to determine criteria for order winning and scheduling at the case study company. The main job scheduling criteria was found to be the value of the job (V), the number of operations to be completed on the job (NO), the engine type (ET), the frequency of the customer (CF) and the relationship between the customer and the company (RR). Time study, company historical records and interviews were used to determine the criteria ranking utilised in the AHP decision making. A multi agent system based on the AHP and EDD and SPT dispatching rules was then developed to automate the decision making process.

4 DECISION CRITERIA FOR THE SCHEDULING SYSTEM

The agent based job scheduling system consists of five main criteria to which the scheduling decision are based on. A pair wise comparison matrix is developed using a scale of numbers that indicates how many times more important or dominant one criteria is over another as shown in Table 1. The scale of numbers used in the pair wise matrix is shown in Table 2. Consistency checks are done as shown in Nyanga et al [14].

	V	ET	NO	CF	RR
V	1	5	3	3	7
ET	1/5	1	1/5	1/4	1/3
NO	1/3	5	1	3	5
CF	1/3	4	1/3	1	4
RR	1/7	3	1/5	1/4	1
Total	2.01	18.00	4.73	7.50	17.33

Table 1 - Pairwise comparison matrix for the five decision criteria

Intensity of Importance	Definition
1	Equal Importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i
1.1–1.9	If the activities are very close

Table 2 - Scale of absolute numbers [13]

	V	ET	NO	CF	RR	Total
V	0.50	0.28	0.63	0.40	0.40	0.44
ET	0.10	0.06	0.04	0.03	0.02	0.05
NO	0.17	0.28	0.21	0.40	0.29	0.27
CF	0.17	0.22	0.07	0.13	0.23	0.16
RR	0.07	0.17	0.04	0.03	0.06	0.07

Table 3 - Normalized pair wise comparison

The normalised pair wise comparison matrix is shown in Table 3.

The consistence ratio (CR) is given by the formula

$$CR = \frac{CI}{RI} \qquad (1)$$

Where CI is the Consistency Index and RI is the Random Consistence Index

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (2)$$

Where λ_{max} the Principal Eigen is value of the pair wise comparison matrix and n is the dimension of the matrix.

Using the column and row totals in Table 1 and Table 3

$$\lambda_{max} = 2.01 * 0.44 + 18 * 0{,}05 + 4.73 * 0.27 + 7.5 * 0.16 + 17.33 * 0.07 = 5.58$$

From Equation 2 and Equation 1, CI= 0.145 and CR =0.13% respectively

Since CR is less than 10% the judgments are trustworthy as stated by Coyle [15].

4.1 Job Value

For the value criteria, the alternatives are bound by the range of income that each job generates into the company. The value is divided into classes depending with the level of contribution of each job. This is done so that the results of the AHP are not totally biased towards the value of the only. Figure 1 shows the relative contributions of each range of values.

Matrix		0-250 1	251-500 2	501-750 3	751-1000 4	1001-1500 5	1501-2000 6	2001-2500 7	2501-10000 8	0 9	0 10	normalized principal Eigenvector
0-250	1	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	-	-	2.36%
251-500	2	2	1	1/2	1/3	1/4	1/5	1/6	1/7	-	-	3.27%
501-750	3	3	2	1	1/2	1/3	1/4	1/5	1/6	-	-	4.77%
751-1000	4	4	3	2	1	1/2	1/3	1/4	1/5	-	-	7.09%
1001-1500	5	5	4	3	2	1	1/2	1/3	1/4	-	-	10.59%
1501-2000	6	6	5	4	3	2	1	1/2	1/3	-	-	15.72%
2001-2500	7	7	6	5	4	3	2	1	1/2	-	-	23.07%
2501-10000	8	8	7	6	5	4	3	2	1	-	-	33.13%

Figure 1 - Contribution for the value alternatives

The system allows the user to enter any value for the job after which the provider agent will use its knowledge of the relative contributions of each amount to calculate the weight contribution of the value alternative.

4.2 Number of Operations

The cylinder head has the maximum number of operations that can be performed compared to the rest of the vehicle engine components. The cylinder head has 18 different operations feasible and is therefore used as reference for the computation of criteria alternative contributions. Table 4 below shows the normalized Eigen vectors and the corresponding number of operations.

Number of operations	2	4	6	8	10	12	14	18
Contribution	36.32	23.71	15.33	9.85	6.31	4.05	2.64	1.78

Table 1 - Number of Operations Alternative Contributions

The fewer the number of operations, the more the job contributes to the total weighting implying that that jobs with less operations are more preferable compared to the other jobs.

4.3 Customer Frequency

The customer frequency alternatives entail the timely distribution of the same customer jobs. These are determined at fortnightly, monthly, quarterly, biannually and yearly intervals of the last jobs. The normalized Eigen vectors for the customer frequency are shown in Table 5 below.

Timeframe	Fortnightly	Monthly	Quarterly	Biyearly	Yearly
% Contribution	4 1 . 2 3	30.26	1 4 . 4 5	8 . 2 4	5.82

Table 5 - Customer Frequency Alternatives Contributions

4.4 Engine Type

The company classified the engines serviced into five groups based on the size of the engine. The engine classes are:

- Passenger
- A – B18, B16 - petrol , minibuses
- B – 22 diesel , 3L , 4L, 5L Mazda-T35
- C – Tractor, civilian, ford, MF
- D – Nissan UD, DAF (mostly buses)
- E – Caterpillar, Cummins and all earth moving equipment

The relative contributions of the engine type criteria are shown in Table 6.

Engine Type/Group	Passenger	A	B	C	D	E
% Contribution	29.6	29.6	18.0	11.2	7.0	4.6

Table 6 - Engine Type Alternatives Contributions

4.5 Customer Relationship

The customer to company relationship is also an important decision criteria. A strong relationship is assigned a +1 whilst a moderate relationship is assigned a +. All neutral relationships are assigned 0s and weak and very weak relationships are given as – and -1 respectively. The percentage contribution of each of these relationship ratings are given in Table 7.

Relationship Rating	-1	-	0	+	+1
% Contribution	4.53	8.19	12.14	25.82	49.33

Table 7 - Relationship Rating Alternative Contributions

5 MULTI AGENT SYSTEM

According to Russell & Norvig [16] an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors. Several methodologies for developing multi agent systems have been discussed by Omicini and Molesini [17], DeLoach [18], Omicini [19], Zambonelli, Jennings and Wooldridge [20], Juan, Pearce, and Sterling [21], Bauer and Muller [22], Nikraz, Caire and Bahri [23], Bellifemine, Bergenti, Caire and Poggi [24]. This paper focuses on the development of the multi-agent system for the job scheduling system using the JADE methodology and Unified Modelling Language 2. The JADE methodology was chosen after a detailed evaluation of the other methodologies as discussed by Dewa et al [25], Singh et al [26] and Nikraz et al [26].

The system consists of a provider agent which is responsible for executing the scheduling of jobs and a job allocator agent which is responsible for assigning these jobs to the machines. The provider agent uses the job weighting in conjunction with the due dates to schedule the jobs and then provide them to the job allocator for allocation to the machines. The provider agent is responsible for providing relevant machining information to the job allocator as well as keeping record of the states of the machines. The agent is also responsible for storing all the relevant information concerning the jobs and the machines to which they will be allocated.

5.1 System Use Case Diagram

According to Bauer and Odell [27] use cases are a means for specifying required usages of a system. The use case diagram for the agent based job scheduling system was developed using the Unified Modelling Language 2.0. Based on the description of the agent-based job scheduling system and after conducting sufficient research and physically observing and assessing the requirements of the system, a preliminary list of possible system functions was built. As noted by Aruväli et al [28] the preconditions for productivity are technological capabilities and human competences. Machinery monitoring can develop both of these preconditions. The use case diagram for the system is shown in Figure 2. Three actors job allocator, operator and scheduling data provider were identified for the system.

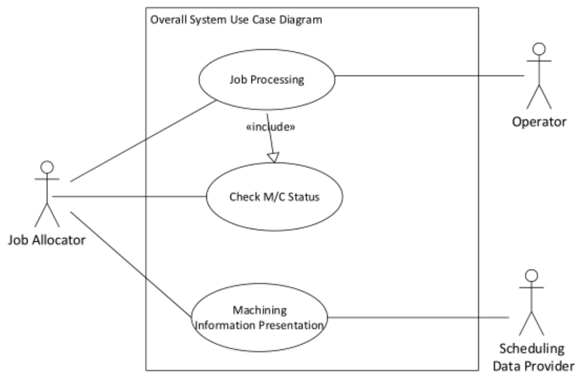

Figure 2 - System Use Case Diagram

5.2 Agent Diagram for the Job Scheduling System

The agent diagram indicates who needs to interact with who as stated by Nikraz et al [26]. The agent-based job scheduling system requires an acquaintance relation between the job allocator agent and the provider agent. Another acquaintance relation is also required between the job allocator agent and the machine state agents. Figure 3 shows the system agent diagram for the system.

The acquaintance relations that exist between the job allocator agent and the provider agent to facilitate retrieval of relevant machining information are also shown in the diagram. Another acquaintance relation exist between the job allocator agent and the machine state agents in order for the

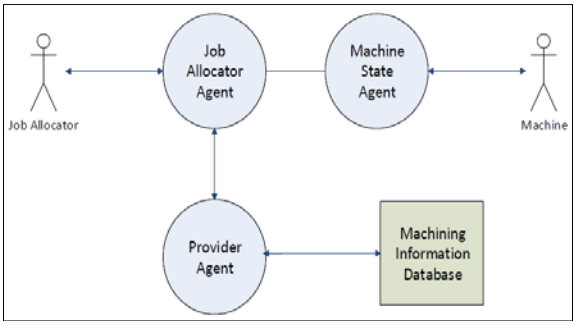

Figure 3 - System Agent Diagram showing acquaintance relationships

job allocator to constantly send jobs to the machines and these are monitored by the machine state agents.

5.3 The Jade Platform

JADE was used to develop the platform since the toolkit is free, open source and is FIPA compliant among the very many advantages and features that it offers. JADE is a software framework which is fully implemented in Java language. JADE simplifies the implementation of multi-agent systems through a middle-ware which complies with the latest Foundation for Intelligent Physical Agents (FIPA) 2000 specifications. There is a broad set of graphical tools provided that supports the debugging and deployment phases of agent development.

6 MULTI AGENT SYSTEM ARCHITECTURE

The multi agent system consists of a society of interacting agents and an external database. The job allocator frequently communicates with the provider agent which plays a vital role in the agent based job scheduling system since it is the one responsible for creating the job schedules. Figure 4 shows the skeletal multi agent system architecture.

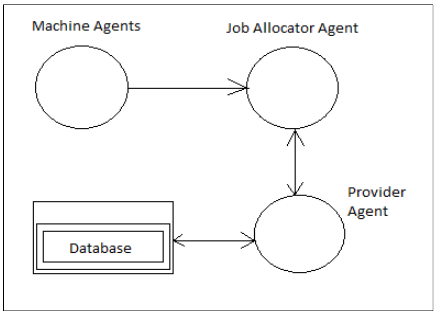

Figure 4 - Multi Agent System Architecture

Information about new job entries is captured through a graphical user interface which captures and stores the data into an external database shown in Figure 5

The utilization of the system, which is the proportion of the available time (expressed usually as a percentage) that a piece of equipment or a system is operating as defined by Hansen [29] is influenced greatly by the system proposed in this paper since bulk of decision making time is substituted by production time.

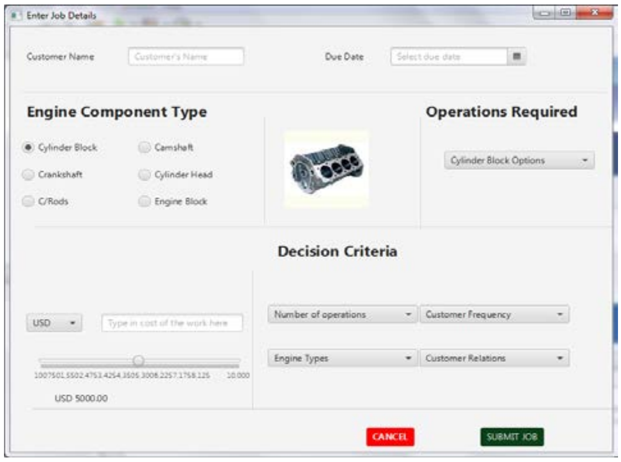

Figure 5 - Job Input Interface

The provider agent is responsible for creating job schedules which it then uses to send jobs to the job allocator to allocate the jobs for processing at the different machines. Jobs with the highest weighting are scheduled first and assigned to machines for processing. If there are two jobs with conflicting weighting, the provider agent uses the earliest due dates in order to give preference to the job with the earliest due date. Figure 6 shows the system allocating a job to a machine and checking the availability of machines.

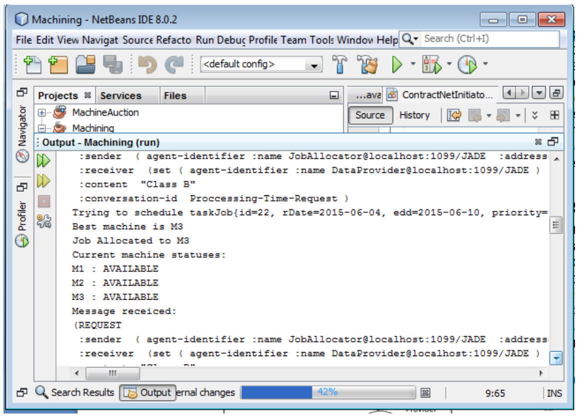

Figure 6 - Job allocation

7 SYSTEM JOB SCHEDULE RESULTS

The multi agent system consists of a main controller interface which collectively gathers all the necessary supporting features for the agent based job scheduling system. The main controller interface allows the user to review the current schedule, search for the various fields including, earliest due dates, date orders were received, completion dates and more. Figure 6 shows the main user interface.

The advantage of using the main user interface is that, all features of the system may be accessed from a single focal point. All the machines can be monitored from this interface as well as a review of the system log which is always available.The system results were compared with the results of the human expect at the comnpany. Average weekly tardness was reduced from two days to half a day.

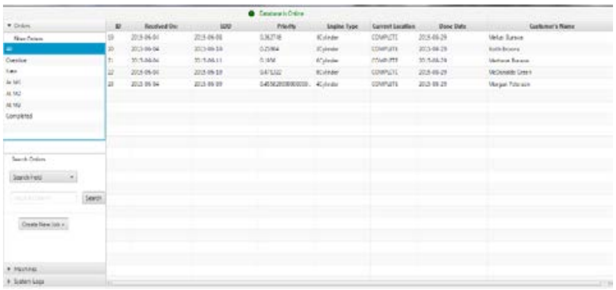

Figure 7 - Main User Interface

8 CONCLUSION

This paper discussed a collective approach to solving the problem related to making decisions when faced with a series of possible alternatives. The agent based job scheduling system, enables the decision to be made concurrently as the jobs are being captured into the system. With the system proposed in this paper, it is quite easy to keep track of all operations, jobs, machines due dates and customers. The chance of making random decisions is eliminated and it is thus easier to keep record of system performance with the view of improvement.

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Comparison of Heuristic Scheduling Approaches in an Energy-orientated Hybrid Flow Shop

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Abstract

The efficient and economic allocation of resources is one main goal in the field of production planning and control. Nowadays, a new variable gains in importance throughout the planning process: Energy. Due to the expansion of renewable energies in Germany, the electrical energy supply is shifting to a complex and volatile system. Therefore, supply and demand need to be synchronized in an efficient way. Companies can profit from capacity based supply conditions and price volatility of the market by implementing the concept of energy flexibility. The main objective is to transform the price signals from the market and the on-site supply into the production planning process. Especially the machine scheduling needs no be enhanced by the factor energy in order to adjust the production demand to a given energy limit. This paper aims to benchmark different basic energy-orientated metaheuristic approaches considering energy flexibility for machine scheduling to a given problem set.

Keywords

production planning and control; energy; machine scheduling; flexibility; hybrid flow shop

1 INTRODUCTION

Energy awareness and efficiency has developed into a crucial success factor in production over the last decades. This success factor is driven both by costs and consumers and is incentivising companies to accentuate energy management within their operations.

In the past, energy as a resource has hardly been considered in production planning and control. It represented a cheap and at all times available commodity, in contrast to other production factors, particularly work force, machine capacity and material [1]. Nowadays, energy has gained in importance since it turned into a changing indispensable and cost-relevant production factor for industrial facilities [2]. This development can be observed on the different energy markets. Apart from the global fossil fuel energy supply, which reserves are limited and thus result in annually peaking prices, electrical energy has changed its characteristics over time as well. Especially in Germany, the industrial sector is facing financial challenges due to high prices for electricity, which have risen by the factor 2.5 between 2000 and 2014 [3]. The reason for this development is the political decision on the German energy turnaround, which resulted in large investments and the expansion of renewable energy technologies, supply infrastructure and grid stability. These are the main drivers among others [3], for new approaches of electrical energy pricing which are designed to encourage production sites to adapt their energy consumption on a daily basis [4].

In addition, the customer perception of "green companies" has gained in importance [5,6]. Therefore, factories are steadily equipped with onsite power generation, both conventional and renewable. In Germany for example, the current share of on-site power generation is 20% from the total industrial power consumption, and the number of installations, particularly renewables, is increasing [7]. Therefore, factories aim at using resources efficiently and at minimizing the environmental impact in terms of their operations [8] within the boundaries of an economically feasible solution. This goal can be attained by implementing the concept of energy flexibility, which enables production systems to align their demand to a given scenario depending on their energy consumption behaviour [4,9].

Within the metal machining industry for example, production resources and equipment with a direct linkage to the production process require 66% to 87% of the factory's overall power needs [10]. In order to enable factories to be adaptive towards volatile energy costs or supply, energy must be integrated as a restriction into processes of production planning and control.

This paper provides a benchmarking of different basic scheduling approaches, which translate the idea of energy flexibility into machine scheduling. Therefore, heuristic methods are used and compared to solve a given problem set by considering energy-orientated restrictions.

2 HEURISTICS IN MACHINE SCHEDULING

In practice, machine scheduling problems are non-deterministic polynomial-time hard (NP-hard) within the class of combinatorial optimization. Therefore, heuristics instead of linear programming are used to obtain a solution. This solution is not necessarily the global optimum, but heuristics tend to find a good solution within reasonable time limitations [11]. Often, metaheuristics are used to handle large and complex systems. Metaheuristics are general strategies which guide the heuristic to solve the optimization problem. Computational approaches, which are using metaheuristics, can be divided into:

- Evolutionary algorithms (EvA)
- Swarm algorithms (SwA)
- Local search algorithms (LsA)

EvA can be described as a population-based stochastic optimization, which is searching a solution space whilst evaluating a set of generated valid solutions. The start of the optimization is a random solution and the chosen algorithm uses the principles of the natural selection, crossover and mutation to generate new solutions within the solution space. The aim is to improve the fitness value of the generated solution, which aligns the optimization goals with the evolutionary principle [12]. A commonly used metaheuristic method is the genetic algorithm (GA).

SwA use an agent-based, decentralized, self-organized system in order to optimize a given problem by a collaborative behaviour of the agents. One example of this behaviour can be found in real ant colonies, which manage to find the shortest way to a food source. Searching for food, ants lay down pheromone trails. Other ants normally follow the path with the highest pheromone concentration. The path with the shortest distance can be completed more often in the same time and the pheromone concentration on this path increases [11]. The ant colony optimization (AC) is another commonly used metaheuristic method.

LsA are designed for improving an initial solution by creating a new solution in its neighborhood using an iterative approach. These algorithms can be seen like a search along a chain of possible solutions [13]. One representative of LsA is the simulated annealing (SA), which simulates the slow cooling of a molten metal in order to receive a perfect crystal structure and a state with minimum possible initial energy. [14]. In contrast to EvA and SwA, LsA have a higher likelihood of leaving local minima. As an example, the temperature function within the SA controls the size of each iteration step and its reduction over time [12].

3 ENERGY-ORIENTATED MACHINE SCHEDULING

The power demand of a factory can be described by the accumulated power needs of every electrical consumer, respectively machines, within the site limits.

A machine’s power demand can be classified by its relation to the production process. Power demands of machines, which are linked to the production process, like a milling machine or an oven, can be described as direct demands. Indirect power demands result from equipment which is not involved in the production process, like air conditioning or illumination [15]. In order to adapt the power demand of a production to a given energy scenario, the machine scheduling is used to plan and optimize the direct demands.

In contrast to energy efficiency or peak load management, energy flexibility requests an adaption during the day according to variable energy prices or availability. For that reason, an energy-orientated scheduling does not necessarily focus on the minimization of the total energy consumption or the minimization of peak loads. In the scientific literature, energy-cost-effective solutions with constant price models and peak load management are widely discussed with regard to machine scheduling problems. In the field of parallel machine problems, Rager developed an approach with a hybrid evolutionary algorithm [16]. Its goal is to reduce the overall energy consumption and therefore the costs by flattening the overall power demand. In another publication, Rager introduced another evolutionary algorithm approach for a variable power supply by avoiding the frequent load alternations that are responsible for the inefficient operation of conversion units [8]. By manipulating the processing speed of the machines, Fang and Lin use a particle swarm optimization for parallel machines in combination with the goal of minimizing tardiness penalty and power consumption [17]. The outcome is a reduction of the power consumption but no possibility of adaption.

Apart from parallel machine scheduling problems, job-shop scheduling under energetic restrictions has been discussed in literature as well. Here, Liu et al. implemented an approach for metal-cutting manufacturing with the goal of minimizing tardiness penalty and power consumption [8]. The approach focuses on the optimization of machines with different machine states, state-individual average power demands and constant processes. The presented result minimizes the stand-by states of the cutting machines in order to generate a cost-effective schedule. With further regard to flow shop problems, Liu, Zou and Zhang developed an optimization model using a genetic algorithm [18]. They compare a make-span-orientated schedule with an energy-amount-orientated schedule. Lou et al. developed another approach which uses an ant colony optimization algorithm for a hybrid flow shop [19]. In every stage of the flow shop parallel machines are available, which vary in speed and power demand. In addition, a varying power pricing model is taken into consideration, namely a time of use tariff.

In summary, energy as a restriction for machine scheduling is steadily changing to a variable factor. Most of the available sources do not take the idea of energy flexibility into account when enhancing existing scheduling approaches. Therefore, an efficient method of an energy-orientated machine scheduling needs to be developed as an organizational approach to implement energy flexibility.

4 BENCHMARKING

In order to find the most appropriate solution, the different approaches need to be benchmarked to a given problem set. To evaluate the results, the following categories are selected:

- Quality of solution
- Restriction Handling
- Computation time

The planning horizon is four days in advance. Therefore, the quality has a higher priority in the evaluation than computation time to find a feasible solution. In addition, the restriction handling is evaluated in order to quantify the effort to adapt the different algorithms.

4.1 Problem set

The problem's exemplary machinery set-up can be described with the following characteristics:

- Four working days, each comprising eight hours of working time and one half-hour-break
- Set number of production jobs, five different variants and different due dates
- Due dates must not be exceeded
- All production jobs have the same machine sequence
- Five machine types with parallel, uniform machines possible; two machines of type two, two machines of type three and three machines of type four
- Up to six different machine states with defined energy demands
- Only defined transitions between the production states possible, e.g. setting up to production
- Different machine capacities greater than or equal to one
- Lots can be split and processed simultaneously on parallel machines. Only complete production jobs can be handed over to the next production step

Fig. 1 shows the production process and the different energy parameters of the machine in operation mode. The given problem is known as a hybrid flow shop (HFS) due to its six production steps, the existence of at least one machine per stage, the existence of parallel machines and due to the same machine sequence needed for every production job [20]. The production planning, where the production jobs and the corresponding machines are combined, is completed four days in advance. The parallel, uniform machines work with constant speed, but the speed of the parallel machines can differ with a constant factor [21]. Because of the different machine states and energy demands, the production system can adapt its overall energy demand flexibly to a certain energy scenario [4]. Before a manufacturing process for a new variant starts, some machine types need to be set up for the new variant. This is why only certain transitions between the different machine states of the machines are allowed.

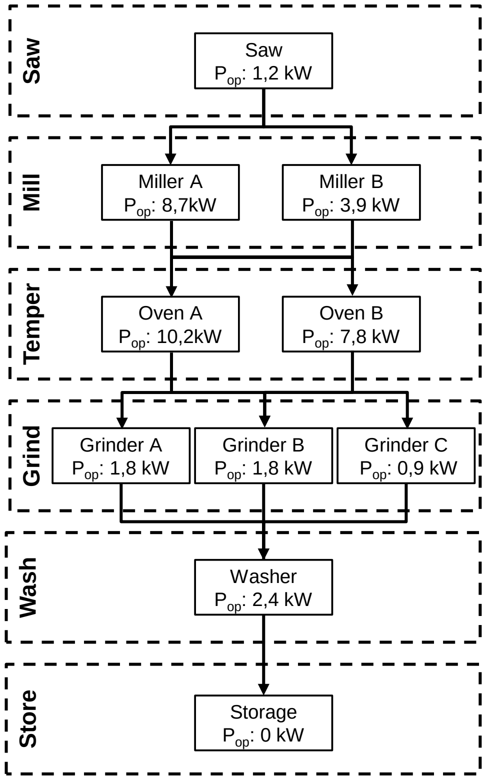

Figure 1 - Machine scheduling set-up

Fig. 2 shows the possible transitions for a machine type with six possible machine states. The main limitation for the optimization is that the due dates must not be exceeded. The required energy flexibility is caused by the slack time of the production jobs and parallel machines with different energy demands.

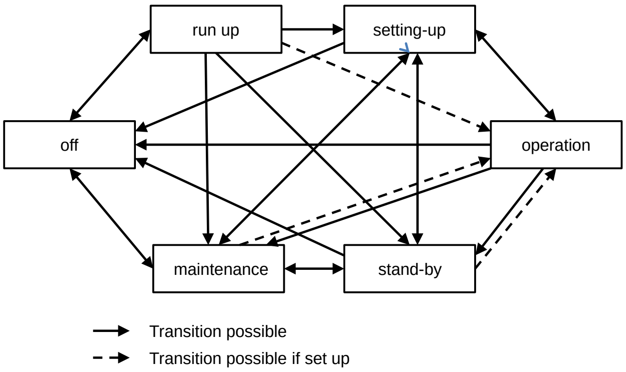

Figure 2 - Possible transitions between the six machine states

4.2 Energy as a restriction in machine scheduling

In terms of machine scheduling, energy can be integrated into the optimization problem in two ways. On the one hand, energy can be viewed as a variable cost factor. On the other hand, it can be considered as a capacity restriction. In practice, energy can be purchased on the market in set capacity blocks, e.g. per hour, or is fixed to a certain tariff of the utility company. In order to translate hourly changing energy prices into energy limits, Fig. 3 illustrates a possible way on the basis of [22]. The algorithm regards the energy limit as a restriction, so the limit is considered as a given capacity that should not be exceeded. If the algorithm uses more energy at a certain time, a penalty payment is imposed which is added to the total energy costs.

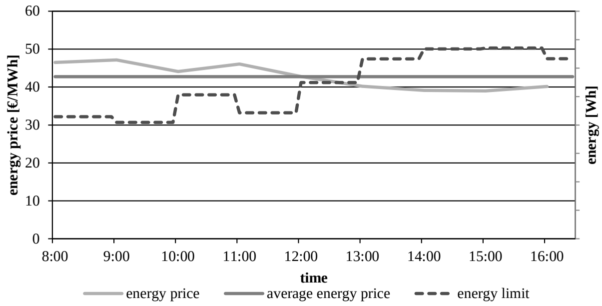

Figure 3 - Example of an energy limit

Within a tariff, the capacity level can be used for pricing in general as well as for the price of the consumed energy to a certain period of time. This information can also be translated into energy limits. In addition to the public supply, the integration of on-site generation into the optimization problem is performed on a capacity-orientated basis. If e.g. renewable on-site energy is available, it can be added to the energy limits. Therefore, the adapted algorithms use energy as a capacity restriction.

4.3 Adaption of metaheuristics

The given problem set is now used to compare the different metaheuristics. Therefore, the three basic approaches presented in chapter 2 must be adapted initially.

4.3.1 *Energy-orientated GA*

At first, an energy-orientated GA is presented as a basis for comparison. The number of the solutions is represented by *i*, which consists of a valid job sequence matrix (*JSM*). The JSM contains the information about which job order is assigned to the machine. Within the decoding, the generated solutions are transferred into a forward scheduling in order to consider shift times, nights and pauses. The fitness value (*FV*) contains the energy costs (*EC*) and is defined as:

$$FV = \frac{1}{EC} \tag{1}$$

Fig. 4 shows the simplified workflow of the initialisation. As defined in chapter 4.1, the due dates of the production jobs have the highest priority and must not be exceeded. This iteration is performed until the maximum number of feasible solutions, e.g. 100, is generated.

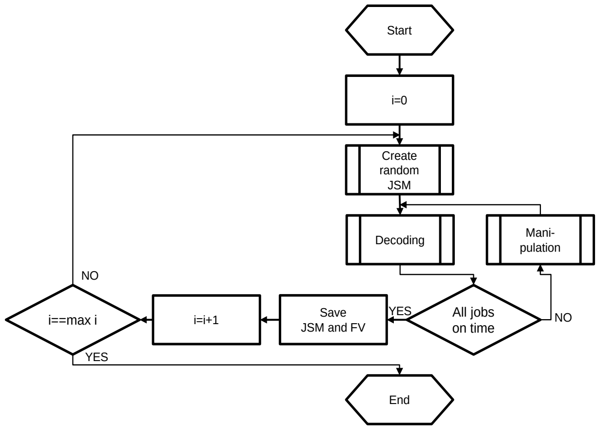

Figure 4 - Simplified workflow of the initialization

After the initialisation, the GA generates new solutions according to the following workflow. At first, the parents, valid JSMs, are selected according to a random function. This function prioritizes parents with a good FV. JOX and SXX represent different successor generations. Only those solutions are recognized which have a higher FV as the average of the existing population. Otherwise the child, a generated solution either with a non-valid JSM or with a low FV is rejected. Fig. 5 shows a simplified workflow of the developed GA.

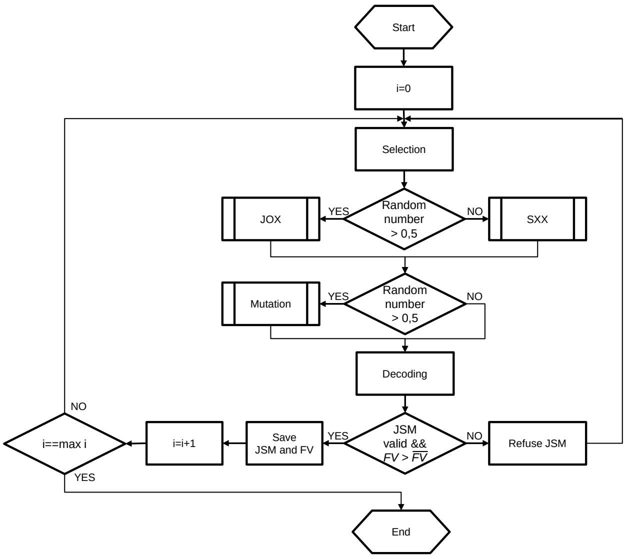

Figure 5 - Simplified workflow of the GA

In a first step, the GA was tested under several energy limit conditions and adapted in detail. In addition, the quality of the solution was investigated in relation to the time needed. Overall, a good solution is generated after approx. 30 minutes computation time. Longer computation times, e.g. 10 hours, have only a marginal effect. Therefore, the GA is a very fast solving approach. Fig. 6 illustrates 23 exemplary runs generating 10.000 solutions GA over time. The results show that the initial solution at an average was improved by 6%.

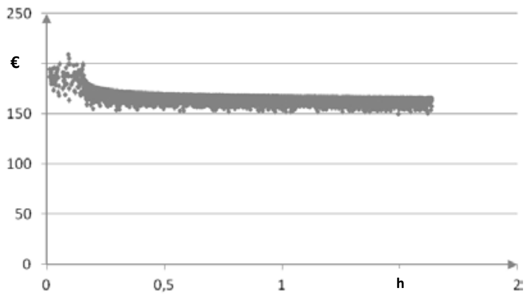

Figure 6 - Results of the 10.000 solutions GA

In a second step, the GA was competing against an energy-orientated AC and an energy-orientated SA. The key results of selected assessments are presented and analysed in the following.

4.3.2 Assessment 1: Energy-orientated AC

At first, the GA is assed to an adapted AC, which uses forward shifting as initialisation and as a basis of the pheromone matrix. For the comparison, twelve production jobs are planned with a varying energy limit over the four days. 20 runs are executed with an average computation time of two hours. A longer computation time for the AC was tested as well but without a significant improvement. Table 1 shows the final results of each approach.

	Energy demand	Energy costs
GA	441,7 kWh	169,1 €
AC	421,4 kWh	192,6 €

Table 1 - Assessment of GA and AC

As a result, the AC needs less energy but is causing more energy costs compared to the GA. In further adaptions of the AC, a better solution can be generated, but it is highly depending on the given solution space. By narrowing down the possibilities, e.g. by blocking machine operations in low capacity times, the AC is finding a better solution compared to the initial forward shifting approach. The same can be observed with the GA. As a result, these adapted metaheuristics can handle an energy-orientated problem set, but both algorithms are limiting themselves to a local minimum too fast. This can be solved by an in advanced optimization of the solution space.

4.3.3 Assessment 2: Energy-orientated SA

In a second approach, the GA is compared to a SA. The developed SA approach uses a cost-based target function, which was enhanced by integrating the energy limit. The initialisation was performed by a Giffler-Thompson-Algorithm. In this assessment, a different energy limit was introduced and the number of jobs was reduced to ten. For the 25 runs of the SA, the average computation time was 12 hours. On the contrary, the average computation time of the GA was 2 hours. Especially the longer computation time leads to a significantly better final solution compared to the initialisation. Table 2 shows the final results of each approach.

	Energy demand	Energy costs
GA	323,8 kWh	75,7 €
SA	348,4 kWh	46,2 €

Table 2 - Assessment of GA and AC

As a result, the SA generates a substantially better solution than the GA, although the GA needs again less energy. This leads to the conclusion that the SA is a preferable metaheuristic as a basis for further research, because it avoids to schedule itself to a local minima.

5 CONCLUSION AND OUTLOOK

The provided benchmark of different basic energy-orientated metaheuristics tried to align energy capacities with a given hybrid job shop scheduling problem with further restrictions. As a result, all metaheuristics were able to improve their initialisation, but in the case of GA and AC, the solution space needs to be pre-optimized in order to leverage the fast solution generation. In contrast to these approaches, the SA offered a significantly better solution, but with a six times longer computation time. Table 3 summarizes the benchmark results relating to the introduction in chapter 4.

	SA	GA	ACO
Quality of the solution	+	o	-
Computation time	-	+	+
Restriction Handling	+	-	-

Table 3 - Assessment of the metaheuristics

In order to generate improved energy-orientated schedules, the SA cost function has to be enhanced in further research. In terms of an improved GA and AC, the capacity planning of the machine hours as a pre-optimization of the solution space is a promising approach. In addition to the improvements, further research is necessary to determine the influence of energy orientation in terms of other production key performance indicators.

ACKNOWLEDGEMENTS

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A Marketing Strategy for a Dry Port in Jakarta/ Indonesia as an Integral Part to Solve Local Logistic Bottlenecks

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Abstract
The Indonesian infrastructure significantly lags behind that of its ASEAN neighbours in both extent and quality, which has contributed to a low level of international competitiveness as well as the lacking internal economic integration and development. The current problems in infrastructure and transport result in higher logistic costs in comparison to most other ASEAN countries. In this fast growing economy, Indonesia's authorities have taken a number of important steps and provided investments to promote a more effective infrastructure development. This study examines and identifies parameters to develop a marketing strategy for the Cikarang dry port (CDP) as an additional logistic hub to the existing, but overloaded Tanjung Priok (TJP) seaport.

Keywords
Logistics, Cost Reduction, Marketing

1 INTRODUCTION

The goal of this study is to develop, evaluate and decide on strategic Business to Business (B2B) marketing strategies in order to increase the capacity of the Cikarang dry port (CDP) in order to relieve the overloaded Tanjung Priok seaport (TJP). This is all directly related to a sustainable support and growth of the Indonesian economy. Therefore, the relationship between Indonesia´s infrastructure, economy and politics will be analysed in detail.

2 RELATIONSHIP OF INDONESIA´S ECONOMY, INFRASTRUCUTURE AND POLITICS

2.1 Economy

As an emerging market with 250 Million inhabitants, Indonesia´s economy has high growth rates. The island nation owns huge occurrences of resources like gold, oil, wood etc. which helped Indonesia´s economy to grow continuously during the last years. Indonesia´s Gross Domestic Product (GDP) experienced high growth rates in the last years. Key economic region is the greater Jakarta. The established ASEAN Free Trade Area in 2010 signed from several South-East-Asian countries will even strengthen the country's economy [1]. In order to ensure the prediction of a GDP growth by 5% for the next years, made by the Worldbank [2], it is necessary to own a corresponding infrastructure.

2.2 Infrastructure

Infrastructure can be defined as a material facility, for example roads, which tries to support and to maximize the potential of the economy. If the economy grows it is necessary that the infrastructure grows correspondingly to it [3]. The Indonesian infrastructure is relatively underdeveloped. It is ranked lower in the Logistic Performance Index from the Worldbank than other comparable ASEAN countries, like Vietnam [4]. Due to the fact that Indonesia´s infrastructure was not growing enough, compared to the economic growth in the last years, the infrastructure affected the economy in a negative way. The results are long transport times and costs, especially in the capital Jakarta, which lead to a lower competitiveness of Indonesian products [1].

2.3 Politics

The Indonesian government recognizes the negative influence that the infrastructure has on the economy and tries to change it. In order to do so, in 2010 the government implemented the Masterplan for Acceleration and Expansion of Indonesia Economic (MP3EI-Plan). The plan invests into several infrastructure projects [5]. The vision is to transform Indonesia into a maritime axis. The focus of the investments lies on maritime elements like ports and shipping [6].

The redirection of the MP3EI-Plan with a maritime character is an opportunity for the country to fix the infrastructure problems in this area, and it would support the economy´s growth. This circumstance underlines the importance of developing strategic B2B marketing strategies for the CDP. The strategies would solve the bottleneck from the TJP and as a result support the growth of the economy in general.

3 FUNCTIONS OF PORTS

In order to understand the function of the CDP and the TJP seaport in a differentiated way, it is necessary to define certain port related terms.

3.1 Ports in general

A port is an area with a water and ground amount where vessels can dock. With the help of terminals, ports are able to handle containers. For example they can lift arriving containers from vessels to the landside. The handled containers per year of a port are declared as handling volume with the unit TEU/year. A TEU is the short term for a 20" standard Container. Over time, ports began to offer more services, such as a disposal for defected goods. This development of strategies is called value added service [7].

3.2 Inland/ Seaport

A seaport is a port that is located on a coast and offers the handling of containers and other value added services. It has an important role in international freight transport. With the help of the port, huge international container vessel ports are able to handle their containers to the landside. In order to do this, seaports offer terminals and customs clearance. A port located on the inland is called inland port. It also has the ability to lift containers for example from a trailer onto an inland vessel [7].

3.3 Dry port

According to a study of the integrating logistics centre networks, a dry port is defined as a port located in the hinterland of an industrial region. Moreover, a dry port is connected with at least one seaport through a rail or road transport and can handle containers. A dry port offers several value added services like customs clearance [8].

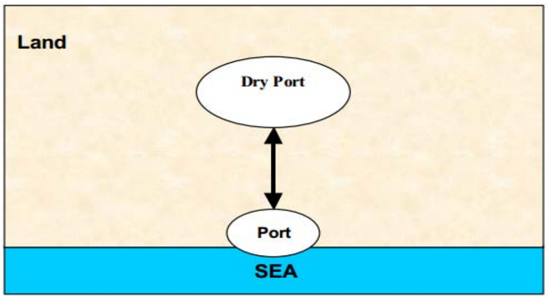

Figure 1 - Concept of a dry port [8].

Figure 1 shows the relationship between a dry port and a seaport. There are two possible ways in which containers can be transported. The first way is to use only a seaport. That means that containers can get to the seaport by trailers for example. After being customs-cleared at the seaport, they are lifted to a container vessel for further transport.

Another possibility to transport containers is to use a dry port. This means that the containers are first transported to the dry port. After being customs-cleared at the dry port, they are transported to the seaport with a trailer or train. Due to the fact that the customs-clearance is already done, the containers can be instantly lifted at the seaport to a container vessel for further transport. This procedure works the same way for containers that should be imported. Thanks to the possibility of doing the customs-clearance at the dry port for containers, the seaport works as a run through station. This ability gives the dry port a relieving function for the connected seaport [8].

4 DUISPORT AS AN EXAMPLE FOR IMPLEMENTED B2B STRATEGIES

4.1 Duisport

The work processes at the Duisport (DP), a German inland port, are an example for the possible implementation of B2B strategies in order to increase the sales at the CDP. First off, the DP is located in Duisburg, Germany, next to an important river, the Rhein. Containers can be lifted from train to trailer and/ or to inland vessels. The DP handles over 3.4 Million TEU/year and is the world's biggest container handling place in the inland. The DP is part of the DP Group, which includes several subsidiary companies. Due to this fact the DP can offer several value added services, like for example: packaging or transporting of goods. Over the years, the DP Group implemented more value added services in order to increase their sales. For example, the implementation of their own transport service [9]. The customer can now organize more required services directly from the DP, instead of organizing these services from different companies. All these value added services help the DP to be more attractive to business customers. The DP is an example to demonstrate a positive implementation of value added services, and also a source to create possible B2B Strategies for the CDP.

5 CONCEPT OF CIKARANG DRY PORT AND TANJUNG PRIOK

5.1 Tanjung Priok seaport

The TJP seaport is the most important port of Indonesia. The handling volume of this port is an indicator of Indonesia´s economy. It handles more than 50% of the imported and exported goods of Indonesia. The most important reason for the bad performance in the processing time is the overload in all kinds of sections. The TJP has a handling capacity of about 5.1 Million TEU/year. In 2014 the port handled round about 6.4 Million containers. This means there is an overloaded of 1.3 Million TEU/year. The result of the overloading is a lack of space, which influences all kind of processes, such as a slow down at the customs-clearance. The customs officers have more trouble to perform a physical inspection. It is forecasted that in the year 2020 the TJP will be even more overloaded [10].

5.2 Cikarang Dry Port

The CDP is a strategic measurement from the Indonesian Government, in order to relieve the overloaded TJP. The CDP was completed 2010 and is able to handle containers. Furthermore, the CDP is connected to a road and a rail network. The CDP is an expansion gate from the TJP in the section of container transhipment.

Figure 2 - CDP bird´s-eye view [11].

The handling volume is about 400.000 TEU/year. The actual utilization is about 25%, so 100.000 TEU/year. Due to the amount of free space (see figure 2) it is possible to expand the capacity to 600.000 TEU/year. The CDP is located 50km away from the TJP in the Bekasi Toll Corridor. This corridor includes over 3.000 industrial companies [12] [13].

5.3 Relieving Function – CDP

The CDP has a relieving function for the TJP. Because of the possibility to perform the customs-clearance for containers at the CDP, it doesn't have to be done at the TJP. If a container uses the CDP for transport, it will receive the customs clearance at the CDP. Then it will be transported to the TJP with trailers.

Figure 3 - Connection between TJP and CDP [14].

After arriving at the TJP the containers will instantly get handled to a container vessel for further transport. The TJP is working as a run-through station for containers coming from the CDP. This procedure is similar to the explanation of a dry port. Therefore the connection between the CDP and TJP is important. The rail connection between the ports is non-functional. The only connection is by road transport (see Figure 3). The transport of containers from CDP to the TJP, is done by a licensed partner transport company. The reason for this licensed company lies in the safety standard of Indonesian customs authorities. To guarantee the safety of the container and customs-clearance, every transported container from the licensed partner transport company is equipped with a special GPS-Lock. Only the special licensed partner transport company is allowed to transport containers between CDP and TJP [13].

5.4 Case study

In order to find out why the customers use the TJP instead of the CDP, it is important to reveal the relative strengths and weaknesses of the CDP. A case study was constructed for this reason, and the results can help to develop customized B2B strategies. The case study analysed a transport of a container from Kaiserslautern, Germany to an industrial company near the CDP. Both transport ways, one time via TJP and one time via CDP, were performed, compared and finally analysed. A strong focus of the analysis was set on the caused costs and the time both transport ways needed. The results showed that the international transport via TJP was around 200US$ cheaper than the transport way via CDP.

The second big difference occurred on the aspect of time. The dwell time, which is the time a container stores on a port before it gets further transported differs, too. At the TJP, it was possible that the dwell time for containers from companies, that were new in the import/ export business, were much higher than at the CDP. Due to the customs regulations the containers from these companies were always getting physically checked at the customs clearance [13]. Because of the overloaded TJP and the lack of space the customs clearance could take much longer compared to the one at CDP. While the customs clearance at the CDP took not more than around 5 days, it could take up to 20 days at TJP.

6 POTENTIAL ANALYSIS B2B STRATEGIES

The knowledge about the relative strengths and weaknesses of the ports was necessary to set up B2B development strategies. Moreover, the strategies can be added to the value added services, such as from the example of the DP.

6.1 Strategy 1

The first strategy tries to remove the weakness of the CDP, which is the higher costs. The aim is to replace the special licensed transport company by a transport company owned by CDP, in order to reduce the higher customer costs at the CDP. This would make the port more attractive to the B2B market and increase the competitiveness. Analyses show that the higher costs are the result of additional costs of the licensed partner transport company, which are necessary in order to transport containers from the TJP to the CDP (and reverse). If the CDP is used for transport, the licensed partner transport

company has to be paid additionally. These costs are overpriced compared to local transport companies. An international transport of a TEU with the CDP is around 200US$ more expensive than the TJP. This could be reduced to 100US$/TEU if a local transport company would be used instead of the licensed partner transport company [15]. The own transport company could be implemented after the contract with the partner company ends. It would transport all containers that have to be transported.

Calculations show that for the 100.000 TEU/year of the CDP around 35 trailers are required. Moreover, for each trailer a GPS-Lock is required to abide to the safety standard of the Indonesian customs authority. The time and quality of the transport will not change because the same route would be used.

6.2 Strategy 2

Another potential B2B strategy is to implement a container repair station. Containers can get damaged by faulty usage of the cranes, e.g. the walls of the containers can get deformed. The probability for damage depends on the modernity of port equipment and also on the skills of the port staff. According to experts, up to 30% of the containers can get damaged in countries like Indonesia [16]. Damaged containers have to be fixed because otherwise it will not get the International Convention for Safe Containers sticker. This sticker is necessary for an international use of the containers.

An implementation of a container repair station would be fast, profitable and inexpensive. Due to the fact that up to 30% of the 100.000 containers, which are handled each year, are damaged, the financial risk is low. The existing extra space from the CDP could be used for building up a repair station. The staff could be trained to search for damaged containers when they handle them. The owner of the containers, which are mostly the shipping lines, could be informed and asked if they want to get them fixed. A further advantage are the low costs for employees in Indonesia. Due to this fact the container repair station could offer services for a lower price for international customers compared to other ports. This strategy offers a new value added service to make the CDP more attractive to business customers.

6.3 Strategy 3

The third strategy is to use the strengths, namely the possibly shorter dwell time compared to the TJP. The marketing department of CDP has to be extended and further trained. The aim of this strategy is to develop an aimed client acquisition. Potential customers should be convinced by the strengths which were identified by the case study. The possibly shorter dwell time should be promoted to those customers who would profit from it the most. In the industrial estates around the CDP, which include over 3.000 companies, companies with time sensible goods have to be approached. Companies can pay high penalties, if their goods arrive too late at their destiny. These kinds of companies have to be identified and convinced that the possible time savings are worth much more than the slightly higher costs of the CDP compared to the TJP. Moreover, the marketing department can promote other possible integrated B2B strategies like the container repair station. The implementation of this strategy could be done relatively fast because it is based on restructuring the marketing department.

7 EVALUATION OF THE STRATEGIES

7.1 Portfolio analyses

In order to evaluate the several strategies, it is necessary to compare them by different criteria, and for this reason the portfolio analyses was used. The three strategies were analysed and categorized by three relevant criteria. The criteria are sales potential, the risk relating to the costs and time, and the market attractiveness. The x-axis represents the risk and the y-axis represents the market attractiveness. The volume of the circles stands for the sales potential of the individual strategies.

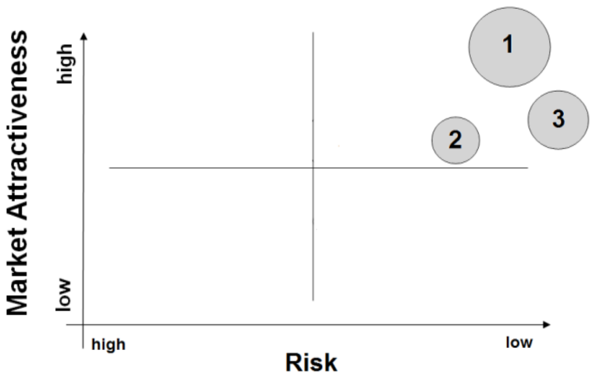

Figure 4 - Portfolio analyses of the strategies [17].

Strategy 1, the replacement of the special licensed partner company, has the highest sales potential and a low risk. The reason is that the 100.000 TEU/year would fully be transported from the new daughter company instead of from the licensed partner transport company. The market attractiveness is also the highest, because this strategy minimizes a huge weakness of the CDP: It will reduce the customer costs. The use of the CDP would cost only 100$/TEU more instead of 200$/TEU, compared to the cost of using the TJP.

Strategy 2, the implementation of a container repair service, has the lowest sales potential from the three strategies. There can be a high potential of the amount of container repairs, but these are mostly not high margin. The risk of this strategy is low and the market attractiveness is high.

Strategy 3, the extension of the marketing department, has the lowest risk of all strategies. Because of the huge number of 3.000 companies around the CDP, there is a huge potential to acquire new customers that do profit from the shorter dwell time of the CDP. The sales potential and the market attractiveness are somewhere in between both other strategies.

In conclusion it can be said that all strategies have a high potential related to the three criteria and should be implemented.

7.2 Benefit analyses

With the help of a benefit analysis it was possible to take a deeper look at the strategies. Just as in the portfolio analysis, different criteria were compared. The difference is that more criteria could be compared. For example, how difficult it is to get the required staff, or the time that is required for an implementation and the costs for an implementation. All these criteria were individually weighted. Based on a calculation and an analysis the three strategies got evaluated on every criterion from 1 (very bad) to 10 (excellent). Each evaluation score was multiplied with the individual weighting of the criteria. The individual results, which are called part utility, were summed up to get a utility score of each strategy.

Criteria	Weighting	Strategy 1 Replacing the partner company		Strategy 2 Container repair station		Strategy 3 Extension of Marketing	
		Assesment	Part Utility	Assesment	Part Utility	Assesment	Part Utility
Sales Potential	25%	9	2,25	7	1,75	7	1,75
Risk	20%	8	1,6	7	1,4	9	1,8
Market attractiviness	20%	8	1,6	7	1,4	7	1,4
Cost for Implementation	15%	3	0,45	7	1,05	7	1,05
Time for Implementation	10%	3	0,3	8	0,8	8	0,8
Required Personal	10%	8	0,8	6	0,6	7	0,7
Utility	100%		7		7		7,5

Figure 5 - Benefit analysis of the strategies

Based on the utility of the strategies it was possible to build a ranking. Strategy 3, the extension of the marketing, has the highest utility based on the criteria chosen. For example strategy 1, the replacement of the partner company, received good results in the portfolio analysis. However in the benefit analysis, which includes more criteria, it scored a 3 in two criteria (see Figure 5).

All in all, the benefit analysis confirmed the result from the portfolio analysis. All three strategies have in general a quite high utility score and should be implemented. Moreover, the benefit analysis can be used to work out a sequence out of the three strategies. For example it is possible to implement strategy 3 first because it has the highest utility and has a low implementation time. Depending on the financial situation of the CDP it is possible to replace the licensed partner transport company or to implement a container repair station.

8 CONCLUSION

The goal to develop a B2B marketing strategy was accomplished. With the knowledge of value added service, dry ports, and the German inland port as an example, it was possible to develop first concepts for B2B marketing strategies. After a detailed look at processes at the TJP and the CDP it was possible to construct a case study. This study revealed several weaknesses and strengths of the CDP compared to the TJP. With this information it was possible to create B2B strategies in order to minimize the weaknesses and to expand the strengths of the CDP. The potential of the three developed strategies were analysed and compared to each other based on several analysis methods. This approach showed that all three strategies should be implemented step after step. Finally these B2B strategies will lead to a higher market attractiveness of the CDP and minimize the bottleneck of TJP. As a result they help Indonesians economy to grow in a more sustainable way having a working infrastructure.

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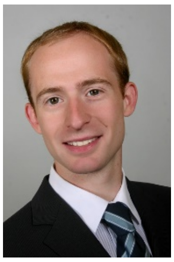

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Eye Tracking usage as a Possible Application to Optimize Processes in the Engineering Environment

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Abstract

Eye tracking is the process of recording a person's eye movement for the better understanding of his/her visual perception. Due to low costs and highly accurate systems the process of eye tracking is used in devices and applications to increase computer interaction and to study human behavior. The technique of Eye tracking is used in a wide range of applications but it is almost absent in the engineering domain. The reason could be that engineering is a very precise science and its product design is based on a rigorous set of physical, functional and legal constraints. This study deals with the usage of the eye tracking technique in the engineering environment. In particular, in this study it was used to optimize the quality assurance of painted utility vehicles, which is a part of the manufacturing chain in the automobile production. The objective of this study was to minimize the time and effort needed to check utility vehicles for paint damages and to reduce the failure rate of not seen damages to the paint.

Keywords

Eye tracking, quality assurance, automobile production

1 INTRODUCTION

1.1. Eye tracking

Eye tracking is the process of recording a person's eye movement for the better understanding of a person's visual perception. Due to low costs and highly accurate systems, the process of eye tracking is used in many devices and applications to increase computer interaction and to study human behavior.

The device used to record the movement of the eye is called eye tracker. It uses projection patterns and optical sensors to determine the eye's position, viewing direction and eye movements with very high accuracy. There are two possible eye tracking systems. One system is directly linked to a screen, whereas the eye tracking glasses are a mobile system, which works with a battery and for this reason it can be used in different environments. [1]

A great majority of eye trackers are based on the principle of corneal reflection tracking. The following measures can be tracked:

- Gaze direction and gaze points, used for the interaction with user interfaces and in behavioral research to determine what attracts a person's attention and for how long. Gaze directions, which last between 200-300ms are cold fixations, whereas saccades describe gaze movements up to 30-80ms. [2]
- Eye presence detection, in this case the eye tracker must find the presence of eyes. It can also be used to trigger devices.
- Eye position is the ability to calculate the position of the eyes in real time. Such features improve the performance of the eye tracker and are also used in gaming and auto-stereoscopic 3D display systems.
- User identification, in this case the eye tracker, is used as a biometric sensor for PC logging or for door operations.
- Eyelid closure is used for monitoring a person's attention span and can be applied for driver assistance or user safety solutions.
- Eye movement and patterns are used to understand human behavior and diagnose diseases. It is possible to run a hearing test on infants. The study of micro saccades is also central in neurological research.
- Pupil size and pupil dilation is used to determine the user's excitement level or the influence of drugs and alcohol.

Eye-tracking has become a powerful tool for understanding human behavior. The eye is directly connected to the information processed by the brain. This provides a simple method to study what a person is thinking. [3]

2 AREAS OF APPLICATION

2.1 Areas of application

There are many areas, where eye tracking is used. Leading consumer goods companies use eye tracking to optimize product packaging and retail shelf design; market research companies and major advertisers use eye tracking to optimize print and TV ads; product companies use it to optimize interaction design; web companies use it to optimize online user experiences and the usability of their websites; universities use it for research in psychology, neurology and medicine. New types of medical diagnostics have also been made possible by eye tracking, as well as safety applications that monitor user attention in critical situations. [4]

Studies using eye tracking can be categorized into four groups [5]:

- Marketing and advertising – in this field eye tracking is used to observe the customer's perception of a product with the purpose of improving the product design so it will be more appealing to the targeted customer group or to verify if a product's label information is being noticed correctly.
- In neuroscience and psychology eye tracking is used to study the effects of various diseases and the behavior, and the decision making process of individuals in various health related cases.
- Computer science and usability – in this case eye tracking is used as an input method for different kinds of devices and software.
- In industrial engineering present and future work environments and processes are analyzed.

In the following parts eye tracking applications in the area of industrial engineering will be focused on.

2.2 Eye tracking - an engineering approach

As shown in the examples above eye tracking is used in a wide range of applications but is almost absent in the engineering environment. One reason could be that engineering is an exact science and product development and design is based on a rigorous set of physical, functional and legal constraints and only after this requirements are met, the visual aspect is taken into consideration.

Examples of where eye tracking can be used in the software environment were given in "Evaluating an eye tracking interface for a two-dimensional sketch editor" where it could be used as another input method for a CAD software to improve the usability. [6]

Another possible use is to record the customer's visual analysis of a prototype and see where the points of interest are. This is useful because it can lead to improvements in the product design beyond the requirements and needs expressed verbally.

It can also be used to analyze how an assembly line worker perceives the working station and if there are any difficulties in locating the tools or mating points of the parts. It also can give a non-conscious feedback regarding the work activity.

Another application for eye tracking is in the quality control faze of a product. If a more complex product is made and the control needs to be done by an employee, his gaze can be recorded and then checked by a computer to see if all key zones of the product were analyzed. [7]

3 EXPERIMENTAL STUDY: QUALITY CONTROL

3.1 Set up

In this study the final quality control of a paint shop of a major European producer of transporters has been analyzed regarding the following aspects:

1. Order/sequence of how the employees of the quality control inspect the transporters in comparison to a given sequence.
2. How long are very sensitive parts/areas of the transporter, which are very vulnerable for damages, inspected?
3. How can the working environment and the work process of the quality control be optimized to improve the working conditions for the employees?

There are three different shifts working on the quality control of the paint shop five days a week 24 hours, including breaks. Taking part in this test was voluntarily for the employees. Because not all people can wear eye tracking glasses and generate useful data, the number of participants was limited. In total, six employees each from the early, late and night shift did participate in the study. Two different kinds of transporters with each two variants in lengths and choice of doors) are manufactured there. The transporter can be produced in 300 different colors. However 90% of them are white.

For the purpose of this study Tobii eye tracking glasses I (60hz, MJPG200 640 x 480) as well as questionnaires and observation sheets have been used. To prepare and evaluate the data, Excel from Microsoft Offices 2013 and the analysis software Tobii Professional 3.2.1 have been selected.

The eye tracking glasses have been used to monitor the employee's eye movement as he/she checked the transporter for damages to the paintwork. Each tested employee did control three transports in a row, wearing the eye tracking glasses. While the employee was checking the transporter, he/she was observed at the same time regarding the following aspects:

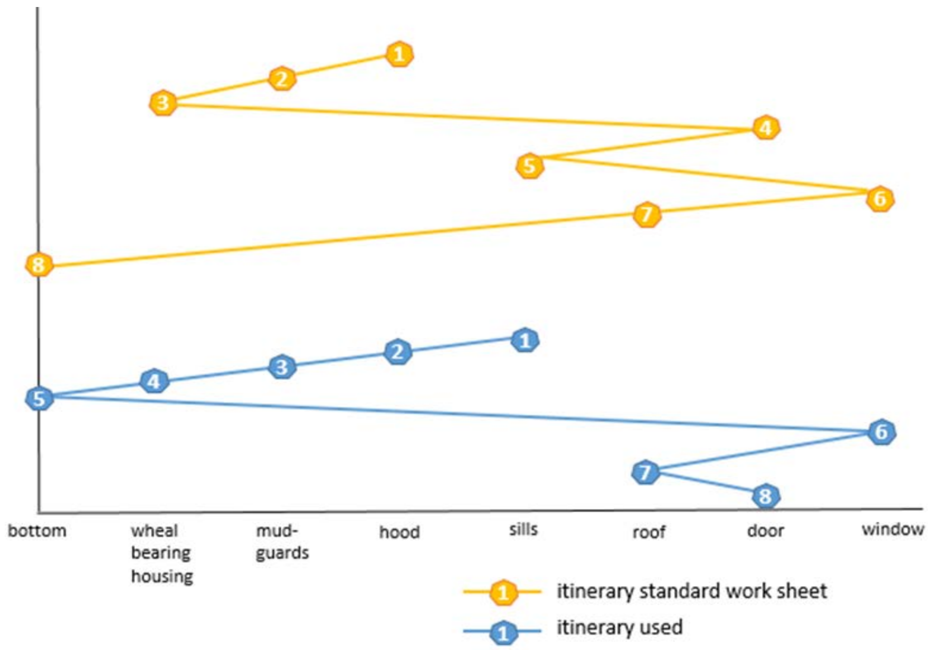

Figure 1 - Overview actual itinerary quality control paint shop

- Transporter (version/color)
- Kind of control (visual/haptic)
- Itinerary

Afterward the tested employee was asked the following questions: [8]

- Experience (years) in working at this part of the manufacturing process
- Rotation within the work process of controlling
- Physical fatigue
- Difficult parts of the transporter to control
- Parts of the transporter with most damages
- Improvements to the working environment

3.2. Proceduere

The study took place at the final quality control at the paint shop within the car manufacturing process of the transporters. There is no given order, in which the different variations of transporters in length and color occur. This means that the production line is flexible enough to produce the transporters on demand. This leads to the fact that the employees working at the quality control of the paint shop have to deal with different variations of transporters all the time.

Furthermore, there is no specified changing modus/rotation modus when the employees change their position within the controlling process. In total 3-4 people are working each at three different control lines, to control the coated transporters. Two employees are checking the transporter for damages to the paint. According to the work instruction for the quality control, which is put on a notice board close to the production line, each employee handles one site of the transporter. Parts of the internal areas of the transporter, which need to be checked as well, are equally divided between the two employees. The other employees handle the checking and repairing of minor damages to the paint.

The collected data will be analyzed with the software Tobii Professional using the following visualization tools:

- Gaze Plot displays gaze data from one or several recordings as single gaze points, fixations, and scan paths. The order and length of fixations can also be visualized
- Heat Map displays gaze data from one or several recordings as a heat map or gaze opacity map. A heat map gives an aggregated view of the results and can be based on fixation counts or gaze time.
- Cluster displays the areas with the highest concentration of gaze points as polygons. [9]

3.3. Data Analysis

In order to receive a statistic of how and in which sequence the transporters are controlled the observation sheets as well as the filmed information from the eye tracking glasses have been analyzed and compared to the given work instruction. An analysis of the eye movement leads to a visualization of their scan paths and allows to display the employee's visual search strategy. [10] Figure 1 shows the given control sequence in comparison to the control sequence performed by the tested employees.

After analyzing the sequences taking by the 18 tested employees, one main itinerary was discovered. The blue line is the sequence which has been used most of the times. It differs from the given control sequence. As a result, the work instruction regarding the quality control needs be revised. The most used itinerary will serve as a base for an improved standard work sheet for controlling the coated transporter.

Statistics naming parts of the transporter, where damages to the paint have often not been found in the quality control of the paint shop are the area around the base of the front passenger seat and parts of the trunk of the transporter. Those damages are often recognized at different quality controls of the transporter at a later time. Finding those damages at a later point of time in the manufacturing process means that there is a delay in time, because the damages need to be repaired, leading to higher production costs. With the help of the eye tracking glasses and the included camera the accuracy of how those parts of the transporter are inspected in general shall be analyzed. To measure the accuracy of how those so called sensitive parts of the transporter are controlled, the time used for checking those parts are compared to the total time used to check the transporter.

For this special matter, the area around the base of the front passenger seat has been analyzed regarding the above mentioned aspects. The Figure 2, filled with the information received from evaluating the films from the eye tracking glasses, shows that all employees tested spent too less time controlling the area around the base of the front passenger seat. An average of 5 out of 116 seconds were used to check this area.

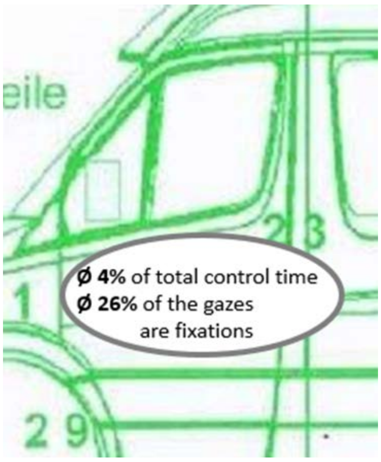

Figure 2 - Results evaluation critical area

Moreover, the evaluation using the Gaze Plot, Cluster and Heat Map analysis, as seen in Figure 3, shows that the employees did not focus and fixate the area long enough and that not all parts, belonging to this area, were looked at. The results of all 16 tested employees revealed that only 26% of the gazes in this area have been fixations.

In the meantime, only saccades were recorded. Only when parts are fixated, optical information can be perceived consciously. [10] As a consequence, the employees should spend more time controlling critical parts, in order to avoid unseen damages to the paint. Possible solutions to approach the above mentioned findings are to train the employees better and to name further control points at the area around the base of the front passenger seat, which need to be checked off.

One important aspect which has been analyzed as well is that how the working environment and the work process itself can be optimized in order to facilitate the work for the employees leading to a lower failure rate in finding damages to the paint of the transporter. The information needed for that was taken from the questionnaires and from the observation sheets. According to the answers of the questioned employees and their given priorities the following two points have been focused on:

- Physical fatigue
- Ideas for improvement of the work environment

Important findings of the questionnaire regarding the physical fatigue were that 60% of the questioned employees said that their eyes were tired after half of their working hours. After mentioning tired eyes, a lack of concentration was named to be a problem after 5 hours of working for 40% of the employees. The quality control is performed equally with the eyes and the hands, no matter how experienced the employees are. The results from the observation sheet show that 85% of the mistakes are found with the eyes. Giving the employees the possibility to name any improvement, four out of nine mentioned ideas considering changes of the light conditions of the work environment. Taking all the findings into consideration, improvements of the light conditions may lead to a better working environment in the way that the eyes will be less tired leading to a higher ability to concentrate and most probably to better results of the employees in general. Furthermore, exercises to relax the eyes shall regularly be included to the quality control and can easily be integrated, when the employees are waiting for the new transporters to arrive. [11]

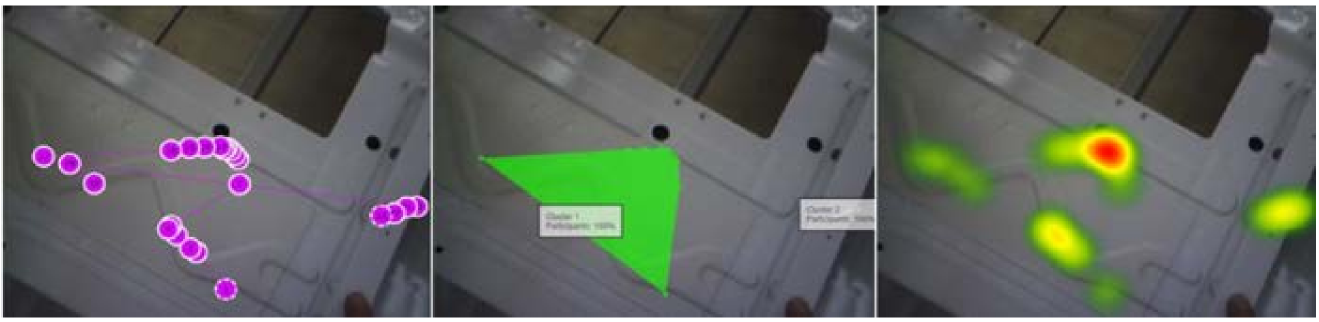

Figure 3 - Visualization controlling area of the base of the front passenger seat

4 CONCLUSIONS

The study shows that using the eye tracking technique as a possible application to optimize processes in the engineering environment is possible. Several useful solutions have been found to optimize the quality control of the paint shop, to improve the work environment for the employees and to minimize the failure rate. Another outcome of the study is that using only the results of the eye tracking glasses is not enough to receive a sufficient answer to complex questions in a manufacturing process. It can only be used as a complement to other evaluation methods.

The following three improvements for suggestions have been concluded:

1. The standardized work sheet for the quality control at the paint shop needs to be adapted to the actual applied itinerary. The mainly applied itinerary shows a more efficient and more comfortable way for the employees. The analysis further indicates, that standardized work sheets need to be adopted and compared to the actual work process regularly.
2. Due to the fact that the results of the quality control could be visualized, the produced pictures and films can be used for enclosed training methods. The collected data can be the basis for a common fault analysis with management and employees. This will eventually lead to a better understanding and adaption of changes of the employees.
3. The results of the questionnaires demonstrate that some major improvement of the workplace environment is necessary. Better health conditions and a further protection of employee's eyes will improve the health conditions, in general, leading to more satisfied employees and a better work outcome.

Concerning the development of lighter and more precise eye tracking glasses, further applications in the engineering environment are possible. It is somehow still a pioneer work, using the eye tracking technology in this area. Already reached results show that there is a great potential, which needs to be built on to set up further standards using this technique.

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6 BIOGRAPHY

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Implications and Future Challenges for Logistics in Cyber-Physical Production Systems at the Example of ESB Logistics Learning Factory

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Abstract
Increasingly volatile market conditions and manufacturing environments combined with a rising demand for highly personalized products, the emergence of new technologies like cyber-physical systems and additive manufacturing as well as an increasing cross-linking of different entities (Industrie 4.0) will result in fundamental changes of future work and logistics systems. The place of production, the logistical network and the respective production system will underlie the requirements of constant changes and therefore sources and sinks of logistical networks have to obey the versatility of (cyber-physical) production systems. To cope with the arising complexity to control and monitor changeable production and logistics systems, decentralized control systems are the mean of choice since centralized systems are pushed to their limits in this regard. This paradigm shift will affect the overall concept under which production and logistics is planned, managed and controlled and how companies interact and collaborate within the emerging value chains by using dynamic methods to generate and execute the created network and to allocate available resources to fulfill the demand for customized products. In this field of research learning factories, like the ESB Logistics Learning Factory at ESB Business School (Reutlingen University), provide a great potential as a risk free test bed to develop new methods and technical solutions, to investigate new technologies regarding their practical use and to transfer the latest state of knowledge and specific competences into the training of students and professionals. Keeping with these guiding principles ESB Business School is transferring its existing production system into a cyber-physical production system to investigate innovative solutions for the design of human-machine collaboration and technical assistance systems as wells as to develop decentralized control methods for intralogistics systems following the requirements of changeable work systems including the respective design of dynamic inbound and outbound logistic networks.

Keywords
Logistics, Cyber-Physical Production Systems, Changeable Work and Logistics Systems

1 INTRODUCTION

Scientist as well as experts and decision-makers from industry agree on the huge potential of the systematic introduction of enabler technologies summarized under the terms “Industrie 4.0” and “Internet of Things” to cope with future challenging globalized market and manufacturing environments [1] [2] [3]. These volatile market and manufacturing environments will be characterized by customized products leading to small lot sizes and the need of changeable production systems which allow a dynamic adjustment of production and logistics processes [4]. Due to their lack of versatility, fundamental changes regarding the technical infrastructure and the required IT-systems for planning, steering and control of changeable production systems are expected. The great significance of logistics in the field of *Industrie 4.0* and the *Internet of Things* is on the one hand based on the rapid technological development and on the other hand highly influenced by technical and social challenges, like the demographic change and urbanization, which are directly or indirectly linked with logistics and a more efficient supply chain management of future value chains [5] [6]. Considering logistics in general, logistics networks including their logistics nodes have to keep pace with changeable production environments, which often excludes the use of conventional logistics infrastructure like statically installed conveyor systems [4] [5]. This evolution to an *Industrie 4.0* implies far-reaching process-related changes as well as substantial investments. Therefore the transition period is expected to last at least one decade and companies will have to develop individual and customized transition concepts in close cooperation with their customers and suppliers [7] [8]. To plan and design these changeable production systems as well as to transfer existing mostly statically designed production into changeable production systems and to develop customized transition concepts specific knowledge and competences are needed [9]. In addition new methods and technical solutions have to be tested and validated in a safe and at the same time practice-oriented factory environment to ensure a smooth transfer into industrial practice. Learning factories, like the ESB Logistics Learning Factory at

ESB Business School (Reutlingen University), offer a wide range of possibilities for research in the field of cyber-physical production systems as well as many options for a practice-oriented education and training of students and professionals in a close-to-reality factory environment. Based on defined maturity levels of the learning factory the participants can be sensitized and trained in the field of cyber-physical systems and at the same time gain specific competences.

2 CYBER-PHYSICAL PRODUCTION SYSTEMS

Future production environments as well as supply chains will be highly influenced by a global crosslinking of all machineries, storage systems and means of production to cyber-physical systems (CPS) respectively cyber-physical production systems (CPPS) [1] [10]. CPPS are networks of at first independent CPS which are creating a comprehensive production system, which is characterized by a high degree of cross-linking of all involved systems representing an independent and intelligent production unit [11]. CPPS also have to be capable of analyzing data in real-time to interact actively with humans as well as digital and physical objects linked to the *Internet of Things* and *Services*. These vertically cross-linked and integrated production systems are a crucial part of the resulting horizontally integrated and real-time optimized value chain networks based on digital consistency of engineering incorporating the product and factory life cycle of entire value chains [9] [11]. Therefore data, services and certain functions will be held, retrieved and executed where the highest benefit, e.g. regarding a flexible and efficient development and production, can be achieved. These places will not necessarily be on the conventional automation levels. This leads to the hypothesis that the today's predominantly existing automation pyramid will be gradually resolved and replaced by interconnected, decentralized systems. In this scenario services, data and hardware components will be spread over various nodes of the emerging network building abstract functional modules which are creating the automation system [12].

2.1 Value networks

Future value chains will be affected by a dynamic and horizontal integration of value networks which organize themselves ad-hoc. Also the intelligent product, which knows its own processing status and possible irregularities of previous processing steps, supports the production process actively, knows its customer and also controls the required logistical processes to its final customer [13]. Therefore a cross-functional digitalization and link-up of value networks is of vital importance. For example in this *Industrie 4.0* scenario the purchasing department will have to track inventories in the own company as well as in the supply network in real-time to keep production running, while the customer will be able to keep track of the degree of completion of his individualized product. So the field of view of companies will have to change from their own factories to the whole value network involving all processes and partners from the engineering, sourcing, production up to the delivery of the final product to the customer [14]. This will also include new methods and processes regarding the use of big data to identify customer needs, predictive maintenance for machineries, the use of open-innovation principles and collaborative engineering to produce products which meet the customer needs and new methods how value chains are designed, organized and costs and earnings are allocated within this dynamic value chains [15] [16].

2.2 Intralogistics systems

The planning and controlling of highly dynamic and changeable material flows of CPPS requires new methods and systems, since a regulation and reconfiguration of the material flow will be required at any point of the material flow system [5]. Today's centrally controlled material flow systems using centralized material flow computers are not capable of accommodating future requirements of tailor-made products, decreasing batch sizes and volatile sales and procurement markets, because these system rely on complex, centralized controller architectures which are neither flexible nor changeable [17]. The combination of changeable production systems and conventional control approaches based on predefined processes would result in a tremendous increase of complexity and a continuous programming effort of central control units like material flow computers [18]. In addition small production batches up to batch size 1 are leading to an increasing number of transport orders which have to be processed and a high complexity of the control systems [19]. The development of decentralized control concepts for automated material flow systems combined with the theories of the *Internet of Things* offer great potential to solve the previously mentioned weaknesses of centralized control systems regarding changeable application scenarios in context with *Industrie 4.0* [18]. The basic units of the *Internet of Things* are cooperating functional units (entities) of conveyor modules, transport units and (software) services which define every automated material flow system [18] [20]. So the goods which have to be transported, route themselves autonomously through the logistical system by using the transport services of the conveyor modules to reach their destination and can be identified and localized anytime within the material flow system. By refraining from the use of centralized material flow computers the complexity of the system can be reduced while the versatility and responsiveness of the material flow system can be highly improved. In addition the solving of arising interruptions and blockades as well as an automated replanning and rescheduling of transport processes and routes are becoming inherent functions of the material flow system [17][18]. Multi-agent systems, which consist of autonomous and cooperating software programs (agents) solving specific tasks based on defined behavior patterns, are often serving as a base technology for the realization of these decentralized material flow control systems. So each conveyor module uses one or more of these agents for a dynamic processing of different tasks like order management and order allocation or route planning depending on the current situation and condition of the logistics system [20]. The control functions formerly found in a centralized, hierarchically structured automation pyramid are transformed into a non-hierarchical material flow system composed of cooperative, intelligent and autonomous entities in *the Internet of Things*. By means of their agents these entities are capable of contacting other conveyor systems, transportation entities and services, are able to exchange and process information and finally to organize and control the material flow autonomously in an optimized manner [17][18]. Conveyor systems, like the FlexConveyor system from the company Gebhardt Fördersysteme GmbH [21], which are following this modular concept mechanically as well as regarding their control systems, are already in industrial application and allow a fast reconfiguration of the conveyor system according to recent requirements.

2.3. Human-Machine Collaboration

Within CPPS employees, machines and resources will communicate and collaborate similar like in a social network, since CPPS will still require the competences and skills of humans as an input as well as employees and executives must be still informed. Therefore the respective roles of employees in line with the technological changes within the production systems will undergo substantial changes regarding the job and competence profiles of the employees [1] [10]. The future role of employees will especially involve their natural capabilities like intelligence, creativity and empathy which hardly can be automated and will also lead to a higher level of responsibility of employees [22]. For example there will still be employees to supervise the superior production strategy or employees who have to act as a creative and specifically skilled problem solver who deals with occurring issues in the CPPS. To do this, the employee will have to be provided with aggregated real-time information to derive actions or interventions and will be assisted by various flexible, partly mobile human-machine-interaction solutions to intervene in the CPPS [23]. But also in the highly technological field of CPPS will be simple tasks for less qualified employees which will not be automated due to economic or technical reasons [24]. To create less burdening work systems and to cope with the intensifying demographic change, innovative technical assistance systems, like collaborative robots, offer a great potential for these manual tasks. Common automation solutions in work and logistics systems are often inflexible, since they are designed for specific operations and changes lead to high programming and configuration efforts and involve a weighing up of automation or flexibility [25]. Also conventional robot systems are designed for stationary use and often require a protective fence to avoid collisions with humans in the work envelope of the robot which militate against a collaborative work of human and robot. Collaborative, force limited robots with intuitive and fast teaching possibilities and integrated safety features are specially designed for a direct and flexible cooperation with humans.

To investigate the industrial feasibility and potential applications in the fields of assembly and logistics of collaborative robots and to train students and professionals on the implementation of these innovative systems, different collaborative robot systems are in use at ESB Logistics Learning Factory.

3 ESB LOGISTICS LEARNING FACTORY

Learning factories offer wide-ranging possibilities for immersive and industry-oriented research, training education. Learning factories in the narrow sense cover a real value chain with a physical product which allows researchers, training participants as well as students to perform, evaluate, and reflect their own actions in a close-to reality research and learning environment [26].

3.1.1 Production system of ESB Logistics Learning Factory

The general objective of the ESB Logistics Learning Factory (LLF) at Reutlingen University is to train students as well as participants from industry the required competences in the field of the design and optimization of flexible and changeable production systems. The production system of the LLF is focused on the assembly of a multi-variant city scooter including the use of innovative technologies like CPS, collaborative robot systems and additive manufacturing technologies. All workstations are mobile and equipped with wireless communication technology and accumulator batteries enabling an easy change of the factory layout. The workstations are also equipped with mobile tablet-pcs, e.g. to receive orders, to send information back to the planning system, to access multimedia-based work instructions or to analyze specific production processes. The access or feedback of information can take place manually or automatically using different maturity levels of information technology, e.g. by using RFID-technology embedded on the product or by using smart sensor tags on the product which are capable of gathering data and act as an intelligent object in the Internet of Things. These technologies set an important step for the development of decentralized control systems in which the product routes itself through the CPPS.

3.1.2 *Knowledge and competence development*

The overall concept regarding the knowledge and competence development of the LLF is composed of defined learning goals and the corresponding learning contents and methods of work and logistics system design, strategies to achieve action competence as well as the learning environment which covers digital tools for an integrated product and process planning and the physical infrastructure to realize the developed solutions. Within the next years the existing production system should be gradually transferred into a CPPS to investigate innovative solutions and methods for the design of human-machine collaboration with a focus on technical assistance systems as wells as to develop decentralized control methods for intralogistics systems following the requirements of changeable work systems. To accomplish a holistic understanding of value networks of CPPS the dynamic design of inbound and outbound logistic networks will also be integrated into the learning factory environment.

3.2 Digital planning environment

The LLF is composed of a digital planning environment and the physical learning factory environment which are interconnected to realize changeable production scenarios (see figure 1).

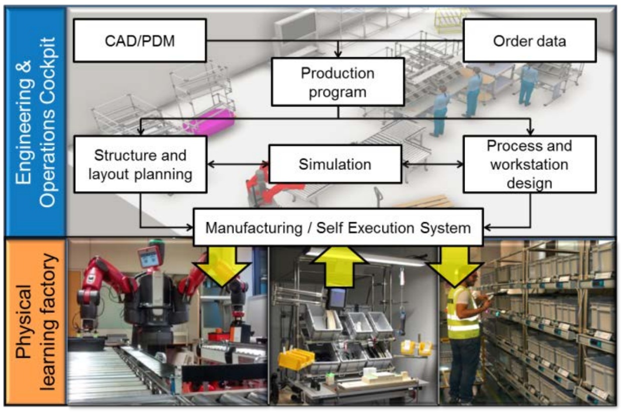

Figure 1 - Digital planning environment and physical learning factory

By using different tools of the software company Dassault systèmes in the so-called "Engineering and Operations Cockpit (EOC)", like ENOVIA for product data management, CATIA for computer-aided design and DELMIA for process and resource planning and simulation, most of the overall required data and functionalities are integrated in the same platform and different production scenarios can be planned and validated with low effort within a short period of time. Customer orders are generated through an online shop, processed by the manufacturing execution system (MES) and finally allocated to the respective resources and workstations in the physical learning factory environment. The information flow is designed bi-directionally to allow the supply of information from the digital planning environment to the physical factory environment as well as vice versa to enrich the planning with current information from the shop floor level. The gathered information is aggregated, analysed and interpreted to optimize und restructure the production system within the EOC to validate improvements digitally before the changes are executed in the physical environment. In addition this digital environment can be used to initiate rescheduling actions or to introduce turbulences (e.g. additional high priority customer orders, malfunction of infrastructure etc.) which have to be solved manually by the participants or automatically by the employed planning and control systems of the EOC. For an improved support of future changeable production scenarios using decentralized control structures and CPS a cloud-based so-called "Self-Execution System (SES)" has been developed and pilot tested in cooperation with a local IT company. The SES has been developed based on an event-oriented concept enriched with a specific cloud data-storage structure for central entities (like employee information) and a digital product memory on every product, for example to allow a decentralized production control and a bi-directional exchange of information between the physical factory and the digital planning environment. Since the SES is still in the proof-of-concept phase and different majority levels should be captured, also a conventional MES is in use to compare the planning and control results of both systems. In a next step also logistical inbound and outbound processes will be integrated into the digital planning environment to simulate the interaction of the learning factory with external value networks to gain an even more realistic learning factory environment and to enable further research in the area of ad-hoc designed value networks in context with *Industrie 4.0*.

3.3 Intralogistics systems

Besides manual pallet trucks and transport trolleys, different kinds of autonomous guided vehicles (AGVs) as well as an intelligent continuous conveyor system are used for material transport. The AGVs can be implemented as both tractors for tugger trains and as a platform for shooter racks to automate the material supply. The routing and navigation of the vehicles is based on optical tracks or laser-based navigation to allow flexible factory layouts. The modular and entirely locally controlled conveyor system, "FlexConveyor" provided by the company "Gebhardt Fördersysteme", is a perfect example of CPS implementation for intralogistics [27]. By means of the plug-and-play functionality and decentralized control units in each conveyor module, the modules can be combined to user-defined conveying lines without the need of a central control entity.

To investigate the potential for automation and/or collaboration in material supply for future CPPS Reutlingen University is going to develop a collaborative tugger train system in cooperation with industry partners in a project funded by the Federal Ministry of Education and Research. The overall aim of the project is the development of an interactive, collaborative and autonomous tugger train transport system including the respective manipulator technology which can navigate through complex factory environments, handle different goods autonomously and can be integrated into the changeable production system of the LLF. To tow the trailers of the tugger train and to manipulate goods a mobile robot platform equipped with a collaborative articulated-arm robot will be used. So the advantages of tugger trains, automation of material supply and human-machine collaboration should be combined. In accordance with the event-oriented and cloud-based concept of the SES a decentralized control method for the tugger train system, based on the approach described in chapter 2.2., should be designed and interlinked with the SES. Based on the knowledge gained within this project, the designed control method will be further developed into a generic method for an autonomous and decentralized control of changeable hybrid intralogistics systems by a dissertation project. So in the long run an autonomous and decentralized control method for changeable production environments should be developed and validated within the LLF which allows the goods to route themselves autonomously through the intralogistics system of the LLF by using different transport systems in an optimized manner.

4 SUMMARY AND OUTLOOK

The global cross-linking of different entities within the respective value networks will result in fundamental changes of future production systems. To reduce the overall complexity of the design and cross-linking of CPPS, reference architecture models like described in [14], which are based on existing standards, are essential to define further fields of research and standardization for a successful transition into *Industrie 4.0*.

Within the next years the complete digital and physical infrastructure of the LLF will be transferred into a vertically cross-linked, decentrally controlled CPPS which interacts with a simulated, ad-hoc generated and horizontally integrated value chain network to serve as an education, training, research and demonstration environment for innovative technological solutions in context with the transition into an *Industrie 4.0*. A major research focus of the LLF will lie in the field of intralogistics systems for CPPS to cope with changeable production environments based on decentralized control methods, innovative human-machine collaboration methods and automation solutions for material supply like the collaborative tugger train system which will be developed, tested and validated under close-to-reality conditions in the LLF.

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Factory Layout Design and Optimisation using PLAVIS "visTABLE"

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Abstract

Due to current economic situations companies are more inclined to increase their profits by increasing production efficiency or by low cost product improvements rather than investing large amounts of liquidities in capital changes. Material flow optimisation is a basic step for many LEAN approaches and its impact on profits is decisive. This study deals with some analytical methods for optimising the material flow and the use of the software PLAVIS "visTABLE" which is an intuitive layout planning program used to optimise, evaluate and visualize the factory layout. With this software it is possible to test and validate layouts immediately by using the integrated planning functions.

Keywords

Material flow optimisation, Lean Production

1 INTRODUCTION

Due to the current economic situations companies are more inclined to increase their profits by increasing production efficiency or by low cost product improvements rather than investing large amounts of liquidities in capital changes. This strategic approach is best represented by the LEAN production philosophy.

"In simple terms, lean means providing your customers with the product or service they desire when they desire it and in the most effective manner possible" [1,2].

LEAN production can be implemented with the following methods:

Value stream mapping is used to trace the material flow between the supplier and the customer for a better understanding and to identify the value-added and non–value-added time of all process steps. After the analysis of material flow, better solutions can be developed and implemented in order to reduce waste and decrease flow time, and to make the process flow more efficiently and effectively.[3,4]

The **5S** approach has its origin in Japan and is characterised by the following words: Sort, Straighten, Shine, Standardize and Sustain. The goal is to improve the efficiency and reduce waste for operations.

MRP is system based on the Master Schedule and it anticipates the time for production or purchase of products based on a defined set of parameters. This method is best used when demand is variable or product and process experience changes. The weak spot is the high volume of accurate data that needs to be processed which may increase costs. [5,6,7]

Just in Time (JIT) and Kanban are applied to stable products and processes, because Kanban is a very reactive system based on actual events and not predictions; it just provides a signal to replace used material.

The **Theory of constraints (TOC)** is based on an effective management of constraints, which need to be identified and which exist long enough so that they can be managed. This system has proven very efficient, but if constrains vary many times per day, it would not be a stable environment.

Material management is a key element for the LEAN systems presented above and for the initial design phase of factory layout. [8,9]

The following study is based on real-life data recorded in one of the largest companies in production of electrical equipment. A team consisting of a professor, an academic staff and a student, worked for about 3 months in this company on the optimisation of material flow. Due to a tight schedule, only the basic functions (rank order clustering) of material flow optimisation could be tested. This study was the perfect introduction into this technology for our research team. All data used in this paper have been provided by the company in compliance with a blocking notice.

2 MATERIAL FLOW OPTIMISATION

2.1 Importance of material flow and process selection

Material management coordinates the flow of material from the supplier through the company and to the customer with the goal of minimising total costs, offering better customer service and using the company's resources to their full potential.[10]

In a simple and clear example it is shown how material management can have a big impact on profits. An income balance from a production company is considered in Table 1 below.

		Euros	Percent of Sales
Revenue (sales)		1 000 000	100
Cost of Goods Sold			
Direct Material	500 000		50
Direct Labor	200 000		20
Factory Overhead	200 000		20
Total Cost of Goods Sold	900 000		90
Gross Profit		100 000	10

Table 1 - Example of income balance

Direct labour and direct material costs depend on the quantity of products sold, but overhead costs are not influenced by the sales. By organising the material flow it is possible to reduce the direct material costs by 1% and the direct labour costs by 5%; the results are shown in Table 2.

The results show a increase in profits by 215%; the same result, without changing direct material and labor costs , would require a increase in sales of €1.2 million. The manufacturing process design and management directly influences the material flow, consequently by optimising the process layout we optimise the material flow. [11,12]

The production system is influenced by product design, volume and available equipment and can be organised in the following ways based on material flow:

- Flow
- Intermittent
- Project

		Euros	Percent of Sales	
Revenue (sales)		1 200 000		100
Cost of Goods Sold				
Direct Material	495 000		41,25	
Direct Labor	190 000		15,83	
Factory Overhead	200 000		16,66	
Total Cost of Goods Sold	885 000		73,75	
Gross Profit		315 000		26,25

Table 2 - Income balance with material flow optimisation

In flow processing parts travel in a successive and constant rate from one workstation to another with no intermittent storage. Implementing a flow process is justified when a high number of parts is processed and when the products of the range are similar or limited. The main benefits are: specialised machinery and tooling, very little inventory build-up, the process is usually automated, which decreases the costs of labour and improves the material flow.

In intermittent manufacturing the products do not flow continuously from one operation to the next, but are made in batches or lots. Furthermore, the large range of material parts demands general purpose manufacturing equipments, which in most cases might not be as time efficient as specialised machinery would be.

The main criteria for selecting the manufacturing process are volume of products and costs. A flow manufacturing system can deal with a large number of parts, but the special machinery is more expensive, therefore a calculation and analysis of all the costs is needed. Fixed costs include the equipment, tools and setup costs and are not influenced by the volume of products. Variable costs include labour and direct materials costs. [10]

$$Variable\ Costs = PT \cdot LC + MC \tag{1}$$

PT is production time, LC labour costs per time and MC is material costs per unit.

The cost per unit (product) is calculated with the following formula:

$$Unit\ Cost = \frac{TC}{x} = \frac{FC + (VC \cdot x)}{x} \tag{2}$$

TC is total costs, FC is fixed costs, VC is variable costs and x is number of units to be produced.

In Table 1 both formulas (1) and (2) are used to show the change in total costs for two production methods, depending on the volume of products. The unit cost for method A is smaller than for method B; but while total costs increase for both methods, there is a point in which the unit cost for method B becomes less then for method A. There is a equilibrium point beyond which the unit cost for method A becomes higher than for method B. This point is very useful when selecting the production method and can be calculated with the following formula:

$$x = \frac{FC(B) - FC(A)}{VC(A) - VC(B)} \tag{3}$$

With the data from Table 1 a graph is plotted showing the cost equalization point.

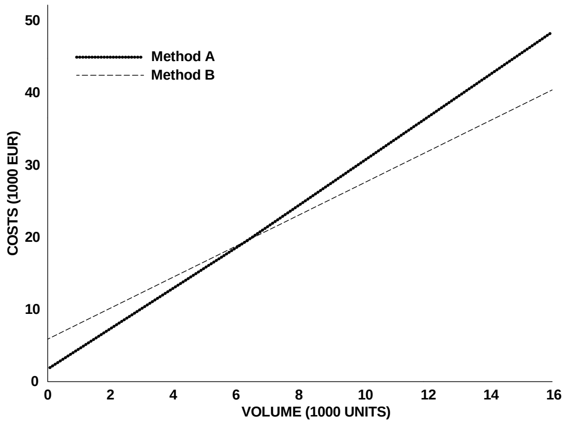

Figure 1 - The Cost equalization point

2. METHODS FOR OPTIMISING THE PRODUCTION LAYOUT

After selecting the process based on the lower total cost, the facility is designed regarding the constrains that are imposed and the experience of the designer. There are a few analytical methods for designing and optimising the layout.

3.1. Rank order clustering method

JOB NR.	MACHINE A	B	C	D	E	F	G	H	I	J
1								X		
2		X	X							
3				X						
4							X	X		
5	X	X	X							
6									X	X
7	X		X							
8						X		X		
9									X	X
10				X	X					
11	X	X	X						X	
12						X	X			
13									X	
14				X	X					
15									X	X
16		X				X	X	X		
17										X
18	X	X								
19						X	X	X		
20					X					

Table 3 - Unclustered operations matrix

Clustering techniques are used to determine part families that share the same set-up idea and equipment, and which follow the same process route. The method's effectiveness is shown in Table 3 and 4.

JOB NR.	MACHINE A	B	C	D	E	F	G	H	I	J
7	X		X							
11	X	X	X					X		
2		X	X							
5	X	X	X							
18	X	X								
14				X	X					
3				X						
10				X	X					
20					X					
12						X	X			
4							X	X		
19						X	X	X		
16						X	X	X		
8						X		X		
1								X		
9			X						X	X
13									X	
6									X	X
15									X	X
17										X

Table 4 - Clustered operations matrix

The clustered matrix can be computed by using only a few lines of code, which makes it an efficient, fast and simple method to use. The algorithm starts by:

- Computing the binary sum for each row of the operation matrix given by the binary weight of the column and the presence of an operation. Afterwards, the rows are ranked in decreasing order, and equal values do not change position.
- If the newly formed matrix is the same as the previous one, the algorithm stops.
- If it is not the same, the next step is to rank the columns based on their binary value; equal columns do not change either.
- Checking again in order to see if the newly formed matrix is identical to the last one; if true, it will stop.
- If not true,it starts again from the first step.

The usefulness/benefit of this algorithm is shown through the following example:

		Part 1	2	3	4	5	6
Machine	A			1		1	
	B		1	1			
	C	1			1		
	D		1	1		1	
	E	1			1		1

Table 5 - Operations matrix

The first step is to reorder the rows:

		Part						Sum	Rank
		1	2	3	4	5	6		
	B.W.	2^5	2^4	2^3	2^2	2^1	2^0		
Machine	A			1		1		2^3+2^1 =10	5
	B		1	1				24	4
	C	1			1			36	2
	D		1	1		1		26	3
	E	1			1		1	37	1

Table 6 - Reorder the rows

For the next step we return to the beginning and rank the rows again.

		Part						Sum	Rank
		1	2	3	4	5	6		
	B. W.	2^5	2^4	2^3	2^2	2^1	2^0		
Machine	E	1	1	1				56	1
	C	1	1					48	2
	D				1	1	1	7	3
	B				1	1		6	4
	A				1		1	5	5

Table 7 - Ranking the rows

The algorithm is stopped because the ranking order is identical. The clustering groups of machines that share the same parts can be easily observed. Oscillations in the ranking algorithm indicate the need to replicate some machines.

4 PLAVIS VISTABLE

visTABLE is an intuitive layout planning program used in order to optimise, evaluate and visualize the factory's layout. With integrated planning functions, it is possible to test and validate layouts immediately. This transparency guarantees the necessary planning security for an efficient and goal-oriented adaptation management.

The software is a powerful tool for production system optimisation and can support the following tasks:

- Plant and layout planning
- Material flow analysis
- Assembly Planning
- Scenario planning
- Running path optimisation
- Setup workshops
- Picking planning
- Implementation of the results of value stream mapping

The software permits the integration of production related experience in order to optimise existing factory layouts by combining first factory design and intuitive operations. The design operation is based on dragging and dropping pre-defined objects, which speeds up and simplifies the process. Furthermore, it is possible to import or create transportation networks and material flow relationships. The standard library contains objects from the fields of building, manufacturing, installation, personnel, transportation, storage, robots, cranes, areas, outdoor areas. Custom models can be created using CAD software (e.g. SolidWorks, 3ds Max, CATIA, etc.) and they can be imported into visTABLE.

Before starting to model the factory layout virtually using the software, a sketch needs to be made of the plant based on the company's requirements. After creating different sketches for the layout, the analysis and comparison of the different designs is done using visTable in order to detect errors and to optimise the process. This represents a big advantage because it is far cheaper to remedy a mistake in the design phase rather than in the following phases. To design a factory plan 6 basic steps could be followed: [6]

- Orient the project
- Classify the parts
- Analyse the process
- Couple into cell plans
- Select the best plan
- Detail and implement the plan

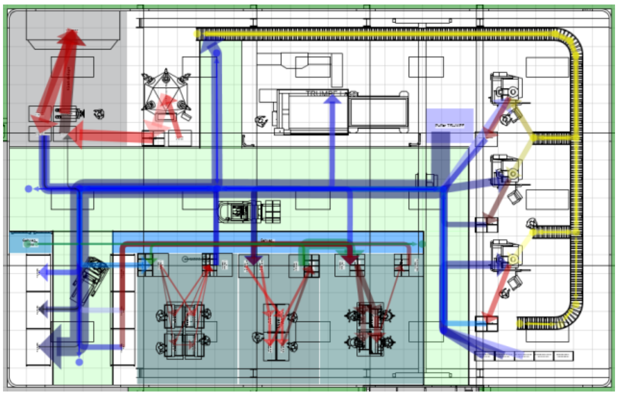

Figure 2 – visTABLE Initial layout

In order to give an example of the advantages of visTable, a production hall layout is modelled and then improved. The equipment used consists of: three DMU 35 and one Metrom CNC machine tool, an manual assembly area composed of three cells, a Trumpf laser cutting machine, an automated vertical storage shelf and a storage area. The moving of the materials is done via three transport routes: a walk way (green), a transport way (blue) and a roller conveyor (yellow), the direct transport is represented with red.

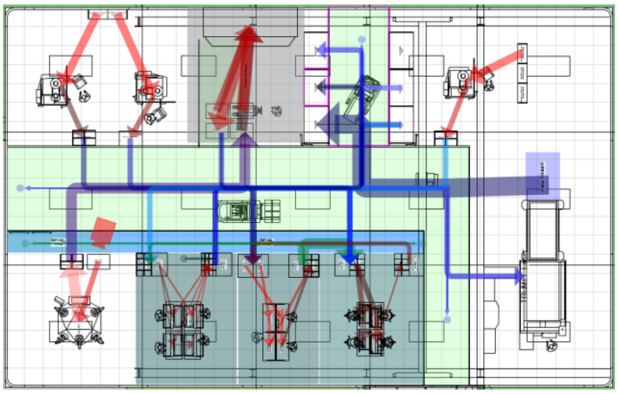

Figure 3 - visTABLE new layout

The initial layout is shown in Figure 4 and the new layout in Figure 5. The automated storage shelf was moved from the top left corner to the top middle zone, and also the storage area was moved from the bottom left corner to the same location so that the distance to the rest of the equipment is more equivalent. The DMU 35 machines were moved from the left side to the top, and two of them were placed one on the left side of the automated shelf and one to the right of the storage area. The roller conveyor was removed and the transport from the automated shelf to the DMU machines is done via the transport way. The laser cutting machine was moved from the top middle area to the bottom right corner and the Metrom CNC machine was moved to the bottom left corner.

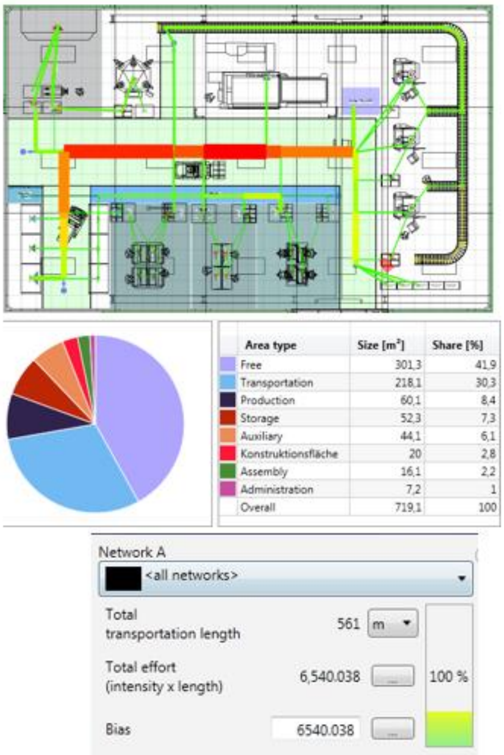

Figure 4 - Analysis initial layout

After a quick analysis the improvements are visible: the transport intensity (number of parts / time) was reduced as shown in Figure 5 to a small zone that leads to the storage area from the main part of the transport way. By eliminating the roller conveyor an improvement was obtained in free area by reducing the transport area and also the total transport length was reduced from 561 meters to 363 meters as shown in Figure 8.

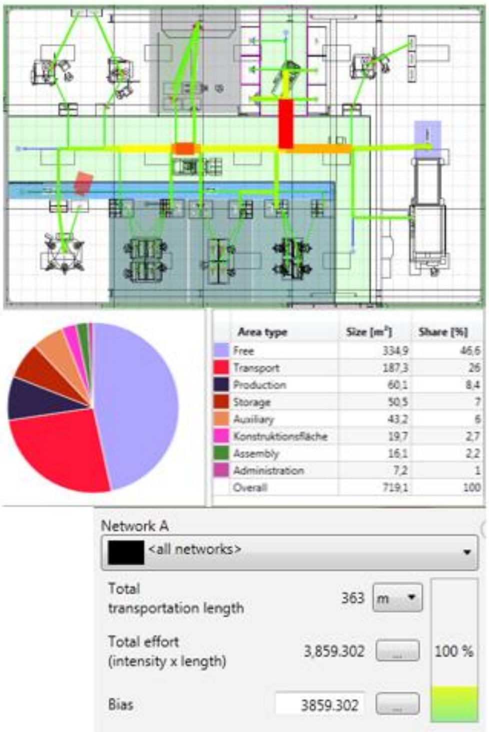

Figure 5 - Analysis new layout

The 3D representation of the layout is a powerful tool provided by the software (visTable) because it gives an accurate preview of the equipment placing and the required safety zones. Furthermore, it gives the designer a better understanding of the work place and facilitates communication with the customer.

Figure 6 - 3D representation

5 CONCLUSIONS

Material flow optimisation is a basic step for many LEAN approaches and its impact on profits is decisive. The optimisation process depends on many factors and usually the solution is based on the designer's experience and intuition. There only a few analytical methods are presented for improving the material flow, but in combination with visTable they provide an effective design mechanism.

Although visTable is not an analytical optimization software to give the best solution based on a set of initial parameters, it does provide excellent support for testing and improving new layouts before they are implemented. The main benefits for using the software are obtained by reducing transport cost and also by eliminating a large part of errors, which are made in the design phase of the project due to a lack of understanding or due to miscommunication between the client and the designer. [15,16,17] Combined with other methods for optimising the equipment placing, visTable gives great results in a short time due to its simple, intuitive drag and drop interface and thanks to the possibility to easily work with colleagues over great distances.

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7 BIOGRAPHY

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An Approach for Modelling the Structural Dynamics of a Mechanical System based on a Takagi-Sugeno Representation

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Abstract
In order to design a controller or run a simulation, an appropriate mathematical model of an investigated system is necessary. Such a mathematical model is also utilized to describe the structural behavior of a mechanical system. Current methods to face the modelling challenges are limited to the description of predefined discrete points of a system. In order to model the mechanical behavior of an arbitrary point along a surface line or within a surface area, we propose an adaption of continuous Takagi-Sugeno Fuzzy Systems (TSFS) for structural mechanical systems. Consequently, the structural dynamics of specific points are modelled in a modal state space representation and utilized as subsystems of the fuzzy system. This approach leads to nonlinear differential equations containing the dynamics of all analyzed points and their interpolation. Thus, a continuous approximation of the properties between the discrete subsystems is possible, thereby outlining the main novelty of this concept. The proposed representation provides the advantages of an TSFS and is also applicable to fields such as model based controller design. The accuracy and performance of our approach is verified by an experimental setup and measurements of the system behavior in the time domain.

Keywords
Takagi-Sugeno Fuzzy System, computational intelligence, structural dynamics

1 INTRODUCTION

Today, models are used in nearly every discipline to characterize a system's specific behavior or its relations. An example taken from biology is the modeling of population dynamics [1]. Within the domain of industrial management, relational models are used to describe numerous influences affecting production [2]. In the field of machine tools, especially considering the cutting process, the knowledge of the structural behavior is of great importance. Such a model can be utilized e. g. for analyzing transient excitation responses or for defining an active vibration compensation controller [3]. The specification of a similar model, which characterizes the structural dynamics of a system using a predefined amount of discrete positions, is state of the art. A good overview regarding this topic is given by [4, 5]. To the best of the authors' knowledge, examination of the structural dynamics within a specified area of an object has not been investigated until now. For this purpose, we propose a method from computational intelligence (CI), an adapted Takagi-Sugeno fuzzy system (TSFS), to achive this goal.

In the past, CI has been applied to a wide range of research tasks in the domain of machine tools, e. g. control tasks [6, 7] or the description of machining processes [8]. An approach for modelling a mechnical system, which partly includes structural dynamics, was presented in [9, 10]. For this purpose, both approaches utilize TSFS. The first publication focuses on a universal specification of the model description. Therein, the authors take advantage of the inherent stability condition of quadratic Lyapunov functions, which analytically guarantees a correct system behavior. This approach is demonstrated using an inverted pendulum on cart as an application example. The second publication is devoted to modeling as well as to controller design. In contrast to [9], the object of investigation is a building. The presented methods were proven to allow a description of the nodal system behavior. The definition of a TSFS in modal representation has not been mentioned. This leads to a model that is capable of specifying the structural dynamics of discrete points. Compared to this, a fuzzy frequency response estimation from experimental data for mechanical structures of aircraft and aerospace vehicles is presented in [12]. The primary objective is to take uncertainties into account and to describe the system's boundaries in magnitude and phase of a bode plot. In the end, this new frequency response estimation can be used for control design and robust stability analysis.

In this paper the proposed TSFS contains the structural dynamics of predefined points and the area inbetween. For this purpose we take advantege of a modal representation, which leads to no changes in the state vector of the interpolated TSFS subsystems.

The remainder of the paper is organized as follows: Section 2 gives a short introduction to structural dynamics and fuzzy systems. In section 3, the novel modelling method is explained in detail. The performance of the proposed approach is confirmed in section 4 by experimental results.

2 FUNDAMENTALS

In this section the differential equations of a mechanical system, the modal state space representation of its structural dynamics and the basics of TSFS are recapitulated.

2.1 Equations of motion

Regarding a mechanical system with N degrees of freedom (dof) and proportional viscous damping the motion equation is as follows

$$\boldsymbol{M}\ddot{\boldsymbol{q}}(t) + \boldsymbol{D}\dot{\boldsymbol{q}}(t) + \boldsymbol{K}\boldsymbol{q}(t) = \boldsymbol{f}(t). \quad (1)$$

Therein, $\boldsymbol{q}(t) \in \mathbb{R}^{N\times 1}$ is the (nodal) displacement vector, $\boldsymbol{M} \in \mathbb{R}^{N\times N}$ is the mass matrix, $\boldsymbol{D} \in \mathbb{R}^{N\times N}$ is the damping matrix, $\boldsymbol{K} \in \mathbb{R}^{N\times N}$ is the stiffness matrix and $\boldsymbol{f}(t) \in \mathbb{R}^{N\times 1}$ is the external load vector. To shorten the notation the explicit formulation of time dependency will not be carried out in the following equations. According to [4] the matrices of the modal parameters natural frequency ω_r, damping ratio ζ_r and mass-normalized eigenvectors (mode shape vectors) $\boldsymbol{\phi}_r \in \mathbb{R}^{N\times 1}$ are defined as

$$\boldsymbol{\Omega} = \begin{bmatrix} \omega_1 & & 0 \\ & \ddots & \\ 0 & & \omega_n \end{bmatrix}, \quad (2a)$$

$$\mathbf{Z} = \begin{bmatrix} \zeta_1 & & 0 \\ & \ddots & \\ 0 & & \zeta_n \end{bmatrix} \text{ and} \quad (2b)$$

$$\boldsymbol{\Phi} = \begin{bmatrix} \phi_{1,1} & \cdots & \phi_{1,n} \\ \vdots & \cdots & \vdots \\ \phi_{N,1} & \cdots & \phi_{N,n} \end{bmatrix}. \quad (2c)$$

Thereby, it is $\boldsymbol{\Omega}, \mathbf{Z} \in \mathbb{R}^{n\times n}$ and $\boldsymbol{\Phi} \in \mathbb{R}^{N\times n}$ with $n \leq N$ as the number of observed modes. By using these parameter matrices subject to the criterions $2\mathbf{Z}\boldsymbol{\Omega} = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{D}\boldsymbol{\Phi}$, $\boldsymbol{I} = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{\Phi}$ as well as $\boldsymbol{\Omega}^2 = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{K}\boldsymbol{\Phi}$ and the modal coordinates $\boldsymbol{q}_m$, which satisfy the condition

$$\boldsymbol{q} = \boldsymbol{\Phi}\boldsymbol{q}_m \quad (3)$$

eq. (1) can be transformed into

$$\ddot{\boldsymbol{q}}_m + 2\mathbf{Z}\boldsymbol{\Omega}\dot{\boldsymbol{q}}_m + \boldsymbol{\Omega}^2\boldsymbol{q}_m = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{f}. \quad (4)$$

This differential equation characterizes the motion of a linear and proportionally viscously damped mechanical system with n modelled (structural) modes. Note, all modal variables are denoted by the index m.

2.2 Modal state space representation

The system described by eq. (4) can be written as the subsequent state space model

$$\ddot{\boldsymbol{q}}_m + 2\mathbf{Z}\boldsymbol{\Omega}\dot{\boldsymbol{q}}_m + \boldsymbol{\Omega}^2\boldsymbol{q}_m = \boldsymbol{\Phi}^{\mathrm{T}}\mathbf{B}\boldsymbol{u} = \mathbf{B}_m\boldsymbol{u}, \quad (5a)$$

$$\boldsymbol{y} = \mathbf{C}\boldsymbol{q} = \mathbf{C}_m\boldsymbol{q}_m, \quad (5b)$$

in which $\mathbf{B} \in \mathbb{R}^{N\times p}$, $\boldsymbol{u} \in \mathbb{R}^{p\times 1}$ and $\mathbf{B}_m \in \mathbb{R}^{n\times p}$ describe the *p*-dimensional input of the system. The *q*-dimensional system output is determined by $\boldsymbol{y} \in \mathbb{R}^{q\times 1}$, $\mathbf{C} \in \mathbb{R}^{q\times N}$ and $\mathbf{C}_m \in \mathbb{R}^{q\times n}$.

Considering a new coordinate vector

$$\begin{aligned} \boldsymbol{x} &= [\boldsymbol{x}_1^{\mathrm{T}} \quad \cdots \quad \boldsymbol{x}_n^{\mathrm{T}}]^{\mathrm{T}} \\ &= [q_{m,1} \quad \dot{q}_{m,1} \quad \cdots \quad q_{m,n} \quad \dot{q}_{m,n}]^{\mathrm{T}}, \end{aligned} \quad (6)$$

where $\boldsymbol{x}_r = [q_{m,r} \quad \dot{q}_{m,r}]^{\mathrm{T}} \in \mathbb{R}^{2\times 1}$, with $r = 1, \dots, n$, contains the modal displacement $q_{m,r}$ and the modal velocity $\dot{q}_{m,r}$. Similar to [5], this leads to the following modal state space representation for the *r*th mode:

$$\begin{aligned} \dot{\boldsymbol{x}}_r &= \begin{bmatrix} \dot{q}_{m,r} \\ \ddot{q}_{m,r} \end{bmatrix} = \begin{bmatrix} \dot{q}_{m,r} \\ \boldsymbol{b}_{\mathrm{m,r}}^{\mathrm{T}}\boldsymbol{u} - \omega_{\mathrm{r}}^2 q_{m,r} - 2\zeta_r\omega_r\dot{q}_{m,r} \end{bmatrix} \\ &= \begin{bmatrix} 0 & 1 \\ -\omega_{\mathrm{r}}^2 & -2\zeta_r\omega_r \end{bmatrix}\boldsymbol{x}_r + \begin{bmatrix} \boldsymbol{0}^{\mathrm{T}} \\ \boldsymbol{b}_{\mathrm{m,r}}^{\mathrm{T}} \end{bmatrix}\boldsymbol{u} \\ &= \boldsymbol{\mathcal{A}}_{\mathrm{r}}\boldsymbol{x}_{\mathrm{r}} + \boldsymbol{\mathcal{B}}_{\mathrm{r}}\boldsymbol{u}, \end{aligned} \quad (7a)$$

$$\boldsymbol{y}_r = [\boldsymbol{c}_{m,r} \quad \boldsymbol{0}] = \boldsymbol{\mathcal{C}}_r\boldsymbol{x}_r, \quad (7b)$$

where $\boldsymbol{b}_{\mathrm{m,r}}^{\mathrm{T}} \in \mathbb{R}^{1\times p}$ and $\boldsymbol{c}_{m,r} \in \mathbb{R}^{q\times 1}$ are the *r*th row of $\mathbf{B}_m$ and the *r*th column of $\mathbf{C}_m$, respectively. The dynamic matrix of the entire system $\boldsymbol{\mathcal{A}} \in \mathbb{R}^{2n\times 2n}$ is given by

$$\boldsymbol{\mathcal{A}} = \begin{bmatrix} \boldsymbol{\mathcal{A}}_1 & & \boldsymbol{0} \\ & \ddots & \\ \boldsymbol{0} & & \boldsymbol{\mathcal{A}}_n \end{bmatrix}. \quad (8)$$

Complementary, the input matrix $\boldsymbol{\mathcal{B}} \in \mathbb{R}^{2n\times p}$ and the output matrix $\boldsymbol{\mathcal{C}} \in \mathbb{R}^{q\times 2n}$ of the modal state space model are defined as

$$\boldsymbol{\mathcal{B}} = \begin{bmatrix} \boldsymbol{\mathcal{B}}_1 \\ \vdots \\ \boldsymbol{\mathcal{B}}_n \end{bmatrix} = \begin{bmatrix} \boldsymbol{0}^{\mathrm{T}} \\ \boldsymbol{b}_{\mathrm{m,1}}^{\mathrm{T}} \\ \vdots \\ \boldsymbol{0}^{\mathrm{T}} \\ \boldsymbol{b}_{\mathrm{m,n}}^{\mathrm{T}} \end{bmatrix}, \quad (9)$$

$$\boldsymbol{\mathcal{C}} = [\boldsymbol{\mathcal{C}}_1 \quad \cdots \quad \boldsymbol{\mathcal{C}}_n] = [\boldsymbol{c}_{m,1} \quad \boldsymbol{0} \quad \cdots \quad \boldsymbol{c}_{m,n} \quad \boldsymbol{0}]. \quad (10)$$

Finally, the eqs. (6) to (10) conclude in the ensuing linear time invariant (LTI) system

$$\dot{\boldsymbol{x}} = \boldsymbol{\mathcal{A}}\boldsymbol{x} + \boldsymbol{\mathcal{B}}\boldsymbol{u}, \quad (11a)$$

$$\boldsymbol{y} = \textstyle\sum_{r=1}^{n}\boldsymbol{y}_r = \boldsymbol{\mathcal{C}}\boldsymbol{x}, \quad (11b)$$

which will be used in this study to describe the structural dynamics of mechanical systems.

2.3 Takagi-Sugeno modelling

Based on the definition of fuzzy sets in [11] and the description of fuzzy systems introduced in [13], a TSFS allows the description of a nonlinear system behavior as a combination of (local) linear systems. The included if-then rules of these TSFS consist of a premise part and a conclusion part. Within the first, the premise variables' degree of membership to the fuzzy sets of the rule is determined. In the second part, functional relationships are formulated, which are combined in a weighted sum. Thereby, the result of each rule is a weighted degree of activation.

Using a notation similar to [14], the ith model rule, with $i = 1, \dots, R$, of a TSFS with linear consequent functions can be stated as

if $p_1 = F_{i,1}$ and ... and $p_L = F_{i,L}$,

$$\text{then} \begin{cases} \dot{\boldsymbol{x}} = \mathbf{A}_i \boldsymbol{x} + \mathbf{B}_i \boldsymbol{u}, \\ \boldsymbol{y} = \boldsymbol{C}_i \boldsymbol{x}, \end{cases} \tag{12}$$

where p_l, with $l = 1, \dots, L$, is the conceivably time-dependent premise variable and L denotes the number of premise variables. Furthermore $F_{i,l}$ is the fuzzy set corresponding to the lth premise variable of the ith rule and the local LTI system dynamic given by the matrices $\mathbf{A}_i, \mathbf{B}_i$ and $\boldsymbol{C}_i$. According to [11] a fuzzy set F is characterized by a membership function $\mu(u)$, which associates each element u out of the universe of discourse U with a degree of membership in the interval $I = [0, 1]$. The activation degree of the ith rule is defined as

$$w_i(\boldsymbol{p}) = \prod_{l=1}^{L} \mu_{i,l}(p_l), \tag{13}$$

where $\boldsymbol{p} = [p_1 \quad \cdots \quad p_L]$ is the collection of all premise variables, which are elements of U and $w_i(\boldsymbol{p}) \geq 0$ as well as $\sum_{i=1}^{R} w_i(\boldsymbol{p}) > 0$. In other words, the and-operator is implemented as the dot product. This leads to the normalized activation degree of the ith rule

$$h_i(\boldsymbol{p}) = \frac{w_i(\boldsymbol{p})}{\sum_{j=1}^{R} w_j(\boldsymbol{p})}, \tag{14}$$

with $h_i(\boldsymbol{p}) \geq 0$ and $\sum_{i=1}^{R} h_i(\boldsymbol{p}) = 1$ due to the normalization. Building on these definitions, the dynamics are expressed as

$$\dot{\boldsymbol{x}} = \sum_{i=1}^{R} h_i(\boldsymbol{p}) \, (\mathbf{A}_i \boldsymbol{x} + \mathbf{B}_i \boldsymbol{u}), \tag{15a}$$

$$\boldsymbol{y} = \sum_{i=1}^{R} h_i(\boldsymbol{p}) \, \boldsymbol{C}_i \boldsymbol{x}. \tag{15b}$$

Generally, the result of this dynamic is nonlinear. It is called a blending of the linear subsystems, in which the weight of each subsystem h_i depends on the premise variables and the fuzzy sets' membership functions. The type of fuzzy reasoning by eqs. (13) to (15b) is named sum-prod inference.

3 TAKAGI-SUGENO BASED MODELLING OF STRUCTURAL DYNAMICS (TSSD)

The goal of this section is to create a TSFS, which is able to model the structural dynamics of a mechanical structure. First, a new matrix is introduced, to link the modal state space representation in eqs. (11a) to (11b) with the well-known receptance transfer function $\boldsymbol{\alpha}(\omega)$. Second, TSSD is developed by setting up an application-oriented TSFS similar to eq. (12) and defining two problem-specific membership functions.

3.1 Connection of notations

Taken form [5] the elements of the transfer function matrix for a proportionally viscously damped system equivalent to eq. (4) are stated as

$$\alpha_{jk}(\omega) = \sum_{r=1}^{n} \frac{\phi_{jr}\phi_{kr}}{\omega_r^2 - \omega^2 + i2\zeta_r\omega_r\omega}, \tag{16}$$

where the indices j and k represent the measurement point and the driving point, respectively. Furthermore ϕ_{jr} denotes the jth element of the mode shape vector $\boldsymbol{\phi}_r$ (rth column of $\boldsymbol{\phi}$ from eq. (2c)). In order to connect this definition with the state space model from section 2.2, eq. (16) is written as

$$\alpha_{jk}(\omega) = \sum_{r=1}^{n} \frac{\mathrm{c}_{\mathrm{m,jr}}\mathrm{b}_{\mathrm{m,rk}}}{\omega_r^2 - \omega^2 + i2\zeta_r\omega_r\omega}, \tag{17}$$

with $\mathrm{c}_{\mathrm{m,jr}}$ and $\mathrm{b}_{\mathrm{m,rk}}$ being elements of the matrices $\mathbf{C}_m$ and $\mathbf{B}_m$, respectively. Note that the equality of eq. (16) and eq. (17) requires one constraint: All elements of the nodal system matrices $\mathbf{B}$ and $\mathbf{C}$, which describe the system's input and output, must be either 0 or 1. Following this constraint, the modal input and output matrices ($\mathbf{C}_m$ and $\mathbf{B}_m$), defined by eqs. (5a) and (5b), are composed of the elements from the mode shape matrix $\boldsymbol{\Phi}$.

Based on this relation we introduce the new matrix

$$\boldsymbol{\Phi}_{ss} = \begin{bmatrix} \phi_{11} & 0 & \cdots & \phi_{1n} & 0 \\ 0 & \phi_{11} & \cdots & 0 & \phi_{1n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \phi_{N1} & 0 & \cdots & \phi_{Nn} & 0 \\ 0 & \phi_{N1} & \cdots & 0 & \phi_{Nn} \end{bmatrix}, \tag{18}$$

where ϕ_{ij}, with $i = 1, \dots, N$ and $j = 1, \dots, n$, are the entries of the eigenvector matrix $\boldsymbol{\Phi}$. Using $\boldsymbol{\Phi}_{ss} \in \mathbb{R}^{2N \times 2n}$ it is possible to calculate the modal state space model written in eqs. (11a) and (11b) directly from the nodal representation, which is more common. Therefore the subsequent equations

$$\boldsymbol{\mathcal{B}} = \boldsymbol{\Phi}_{ss}^{\mathrm{T}} \begin{bmatrix} \mathbf{0}^{\mathrm{T}} \\ \boldsymbol{b}_1^{\mathrm{T}} \\ \vdots \\ \mathbf{0}^{\mathrm{T}} \\ \boldsymbol{b}_{\mathrm{n}}^{\mathrm{T}} \end{bmatrix} \text{and} \tag{19}$$

$$\boldsymbol{\mathcal{C}} = [\boldsymbol{c}_1 \quad \mathbf{0} \quad \cdots \quad \boldsymbol{c}_n \quad \mathbf{0}]\boldsymbol{\Phi}_{ss} \tag{20}$$

show the link between the two representations.

3.2 Definition of TSSD

Relying on the presented theory in the previous sections we want to apply TSSD to a mechanical system described by the eqs. (5a) and (5b) as well as (11a) and (11b), respectively. Thereby, each pair of measurement and driving points is represented by one subsystem. This leads to the final TSSD representation in which the ith rule of the TSFS is stated as

if $\boldsymbol{p}_{in} = F_{i,in}$ and $\boldsymbol{p}_{out} = F_{i,out}$,

$$\text{then} \begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{\mathcal{A}} \boldsymbol{x} + \boldsymbol{\mathcal{B}}_i \boldsymbol{u}, \\ \boldsymbol{y} = \boldsymbol{\mathcal{C}}_i \boldsymbol{x}, \end{cases} \tag{21}$$

where $\boldsymbol{p}_{in}$, $\boldsymbol{p}_{out} \in \mathbb{R}^3$ are the premise variables of each rule and $F_{i,in}$ as well as $F_{i,out}$ are the fuzzy stets of the ith rule, describing the geometric area of the measurement and driving point.

This system operates in the following way: Prior to the application of the presented approach, the user determines a set of transfer functions at specific points on the test object's surface. Combined with the membership functions, these points shape the fuzzy sets $F_{i,in}$ and $F_{i,out}$ for all *i*. Depending on the measurement and driving points, the premise variables have a specifiable degree of membership to all fuzzy sets. The final outcome is the displacement vector $\boldsymbol{y}$, which results from the weighted sum of all linear subsystems described by eq. (21). It is important to note, that in this eq. the dynamic matrix $\boldsymbol{\mathcal{A}}$ is independent of the fuzzy rules. As a consequence, no state of $\boldsymbol{x}$ changes its physical sense, which is a fundamental requirement of a TSFS. Because of a possible blending between the subsystems an approximation between the analyzed points becomes available.

Since the transfer function is linear, switching the measurement and the driving point does not make a difference theoretically. Because of the utilization of a state space representation, every possible combination has to be taken into account to guarantee a fixed meaning of $\boldsymbol{x}$. As a conclusion, the number of rules for a fully described network is calculated as $\mathrm{R} = P^2$. Furthermore, P denotes the combined number of measurement and driving points, which have been determined by the user beforehand.

In the proposed approach, every fuzzy set is defined to have the same type of membership function, which has a significant influence on the final result. Before defining two function prototypes, we set up five requirements, which have to be fulfilled by every membership function:

1. The image region of a membership function covers the whole interval $I = [0, 1]$.
2. A membership function is continuous.
3. The core of each fuzzy set consists of exactly one unique element, which is determined by a measurement point or a driving point. This specific point in space is described by the vector $\boldsymbol{p}_{core,l} \in \mathbb{R}^3$, with $l = 1, \dots, P$. It is the only element of the fuzzy set F_l, whose degree of membership is equal to 1. Since $\boldsymbol{p}_{core,l}$ is specific for F_l, the intersection of two fuzzy sets' cores has to be the null set.
4. If the Euclidean distance between an examined point $\boldsymbol{p_e} \in \mathbb{R}^3$, i. e. one of the premise variables from eq. (21) and the core of an arbitrary fuzzy set $\boldsymbol{p}_{core,l} \in \mathbb{R}^3$, with $l = 1, \dots, P$, decreases monotonously, then the associated degree of membership has to increase monotonously.
5. For every element in the universe of discourse, i. e. for every point on the surface of the object, the sum of all degrees of membership is equal to 1. This can be regarded as a normalization, as mentioned in [14].

Due to the restrictions above a fuzzy set, e. g. F_l with $l = 1, \dots, P$, is characterized and named by its core element $\boldsymbol{p}_{core,l}$, which is equal to the vector $\boldsymbol{p}_l$ representing the specific point. If a measurement or driving point is used in multiple rules, then the associated fuzzy set, i. e. the membership function has to be identical. This is also true for the case that a point is once used as a measurement point and another time as driving point. Therefore, the total number of points P is equal to the total number of fuzzy sets in the TSFS defined by eq. (21). The Euclidean distance between two points in space $\boldsymbol{p}_i$ and $\boldsymbol{p}_j$ is written as d_{ij} henceforth.

3.3 Membership function concepts

This section introduces two new concepts of membership function, which are supposed to fulfill the five aforementioned constraints. In addition to the definition, the function prototypes will be examined in a two-dimensional test environment.

3.3.1 Membership function concept 1

It is $\boldsymbol{p}_e \in \mathbb{R}^3$ the vector of the examined point, which can be any point on the object surface. The collection of all considered fuzzy sets is called termset of the linguistic variable $\mathcal{X}$ and denoted as $\boldsymbol{T}(\mathcal{X})$ [15]. Thereby, F_1 is the first of the P fuzzy sets and the last one is F_P. The membership function of the fuzzy set F_i, with $F_i, F_j, F_k \in \boldsymbol{T}(\mathcal{X})$, is defined as

$$\mu_i(\boldsymbol{p}_e) = \frac{\prod_{F_j=F_1,\, F_j \neq F_i}^{F_P} d_{ej}}{\sum_{F_k=F_1}^{F_P} \left(\prod_{F_j=F_1,\, F_j \neq F_k}^{F_P} d_{ej} \right)}. \tag{22}$$

Expressed in words, the eq. (22) states: The degree of membership of the point $\boldsymbol{p}_e$ to the fuzzy set F_i, defined by the point $\boldsymbol{p}_i$, is calculated by a ratio of distances in space. In eq. (22) the numerator holds the product of the distances from the examined point to all other points, which characterize the considered fuzzy sets. The denominator uses the same calculation rule for all fuzzy sets in $\boldsymbol{T}(\mathcal{X})$ and sums up the results.

3.3.2 Membership function concept 2

Under the same conditions as mentioned in the previous subsection, the membership function of the fuzzy set F_i is defined as

$$\mu_i(\boldsymbol{p}_e) = \begin{cases} \dfrac{1 - \dfrac{d_{ei}}{\hat{d}_i}}{\sum_{F_j=F_1}^{F_P} 1 - \dfrac{d_{ej}}{\hat{d}_j}} & \text{for } d_{ei} \leq \hat{d}_i, \\ 0 & \text{for } d_{ei} > \hat{d}_i. \end{cases} \tag{23}$$

with the parameter $\hat{d}_i$ defining a distance where the point i has an influence on the approximation of the examined point. Thus, this function prototype generates a seemingly piecewise linear relation between the distance and the degree of membership. However, due to the dependency of the Euclidean distances from $\boldsymbol{p}_e$ to the core elements of the fuzzy sets, which change simultaneously, the membership function in eq. (23) is nonlinear. In each case the distance of the examined point to one of the fuzzy set's core elements equals or exceeds the associated distance parameter, the slope of $\mu_i(\boldsymbol{p}_e)$ decreases.

Both of the introduced function prototypes fulfill all of the previously listed conditions and lead to nonlinear functions, that return the value 1 if $\boldsymbol{p}_e = \boldsymbol{p}_i$ and the value 0 if $\boldsymbol{p}_e = \boldsymbol{p}_j$ with $j = 1, \dots, P$ and $j \neq i$. The fifth requirement implies the benefit, by implementing this TSFS in software using one state-space system.

3.3.3 Test of the membership function concepts

Consider a not further specified arbitrary triangle in space, illustrated in figure 1. The points A, B and C mark the vertices, whereas M is the circumcenter. Because of this fact it is $d_{AM} = d_{BM} = d_{CM}$. Furthermore $\boldsymbol{r}$ indicates the direction in which a point T moves from M to A over the normalized time τ with a constant velocity. Therefore, this scenario yields a strong relationship between the normalized time and the distanced between the point T and the vertices. There exist three fuzzy sets F_A, F_B and F_C defined by their core elements $\boldsymbol{p}_A$, $\boldsymbol{p}_B$ and $\boldsymbol{p}_C$ as well as their membership functions $\mu_A(\boldsymbol{p}_T)$, $\mu_B(\boldsymbol{p}_T)$ and $\mu_C(\boldsymbol{p}_T)$, which depend on the test case.

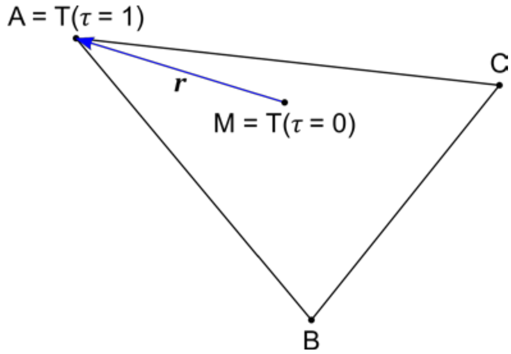

Figure 1 – Test environment for function prototypes

Due to the chosen setup the degree of membership from $\boldsymbol{p}_T$ to all fuzzy stets at $\tau = 0$ is $\frac{1}{3}$. In analogy to that the degree of membership at $\tau = 1$ is 1 for F_A as well as 0 for F_B and F_C. The two subsequent figures visualize the behavior of the different function prototypes from subsection 3.3.1 and 3.3.2, respectively.

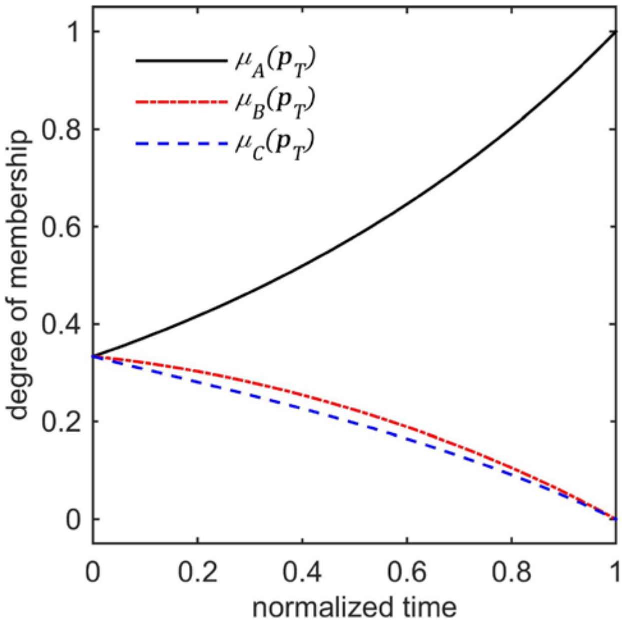

Figure 2 – Membership function concept 1

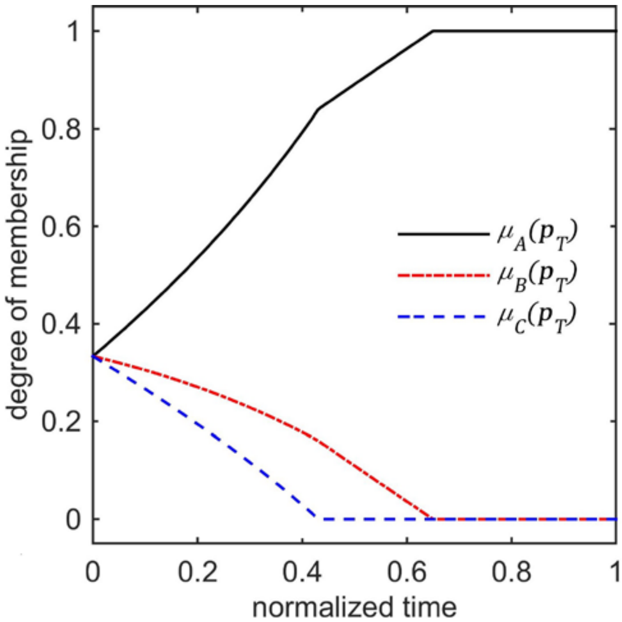

Figure 3 – Membership function concept 2

The figures 2 and 3 illustrate, that the two concepts of membership function fulfill all mentioned requirements. In case of the second concept, the distance parameters for all the fuzzy sets have been chosen equally as well as larger than the initial distance from the circumcenter and smaller than each side of the triangle. This determines the time in figure 3 at which $\mu_B(\boldsymbol{p}_T)$ and $\mu_C(\boldsymbol{p}_T)$ become zero. As mentioned beforehand, both function prototypes show a nonlinear characteristic.

4 APPLICATION OF TSSD

The validation of this approach was done by evaluating a series of measurements, which were carried out on an approximately two-dimensional steel plate mounted on four steel springs at the edges of the plate. The measurement points were arranged in a triangular grid shown by figure 4. Each side of the equilateral triangle is $100\,\mathrm{mm}$. The points B, C, D and F mark the midpoint of the related lines. The driving point O (also measured) was located at the position $\boldsymbol{p}_O = [10\,\mathrm{mm} \quad 10\,\mathrm{mm} \quad 0\,\mathrm{mm}]^\mathrm{T}$ and the measurement point A was placed at $\boldsymbol{p}_A = [100\,\mathrm{mm} \quad 100\,\mathrm{mm} \quad 0\,\mathrm{mm}]^\mathrm{T}$ in relation to the global coordinate system. Note, that the positions of the points on the test surface as well as the relative positions of these points were chosen arbitraryly.

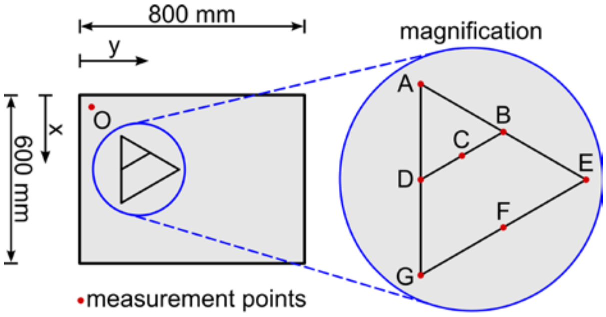

Figure 4 – Sketch of the steel plate (top view)

The goal was to show the performance of TSSD by comparing the measured system response of a specific point (here C) to the results computed by the TSFS in eq. (21) and the measured system response of the nearest point. The defined TSSD contains the dynamics of all illustrated points in figure 4, except C, resulting in 49 rules. As a measure for similarity the root mean square (RMS) was used. Considering two discrete signals $y_{des}[k]$ and $y[k]$ with K samples, the RMS of their difference $y_{diff}[k] = y_{des}[k] - y[k]$ is calculated as

$$RMS\big(y_{diff}[k]\big) = \sqrt{\tfrac{1}{K}\textstyle\sum_{k=1}^{K} y_{diff}^2[k]}. \tag{24}$$

This is a nonlinear measure, where big deviations have a disproportionately high impact.

Concerning the simulation, the inputs of all subsystems are the same recorded force excitation values provided by an impulse hammer. The outputs of the systems were calculated based on the modal parameters, which have been extraced beforhand. The results of the different TSFSs will be compared to three reference systems. They were chosen because of their minor deviation from the desired system behavior. Moreover the measurement points of the reference systems are the three closest to the measurement point of the target system. The approximation results of the transfer function from $\boldsymbol{p}_O$ to $\boldsymbol{p}_C$ are summarized in table 1. The contained index describes the output point, whereby y_{c1} and y_{c2} represent the results for TSSD using both membership function concepts from section 3.3. For each signal the driving point was O, hence it does not show up in the notation of the signals. This example of application represents a special case, because the described theory allows a continuous and erratic shifting of measurement and driving point. The last two columns of the table contain the RMS values of the deviation from each system's output to the true output y_C, in which lower numbers represent a better approximation. The evaluation includes the examination of two different time intervals. The point in time $t = 15\,\mathrm{s}$ is of interest, because the amplitude is down to less then $50\,\%$ of the initial peak value. At $t = 150\,\mathrm{s}$, the amplitude has decreased to less then $2\,\%$ of the initial peak value. These two statements apply to all signals.

signal	parameter	$RMS(y_C - y_i)$ $[10^{-6}\,\mathrm{m}]$	
		$t_{end} = 15\,\mathrm{s}$	$t_{end} = 150\,\mathrm{s}$
y_A	–	13.73	4.686
y_B	–	13.77	5.463
y_D	–	15.46	6.172
y_{c1}	–	10.47	4.093
y_{c2}	$\hat{d}_C = 51\,\mathrm{mm}$	10.77	4.426
y_{c2}	$\hat{d}_C = 101\,\mathrm{mm}$	10.21	3.948
y_{c2}	$\hat{d}_C = 151\,\mathrm{mm}$	10.27	3.974

Table 1 – Comparison of the RMS values

Table 1 shows that both concepts of membership functions (outputs y_{c1} and y_{c2}) perform better than all three reference systems (outputs y_A, y_B and y_D). For better readability, the best result of TSSD and the reference systems have been highlighted for each time interval. In contrast to the first membership function prototype, the second is adjustable by the distance parameter $\hat{d}_C$. Increasing this parameter leads to a consideration of more subsystems, i. e. to a larger number of rules. Once $\hat{d}_C$ exceeds the largest appearing distance between the examined point and one of the measurement points ($d_{CG} = d_{CF}$), the effect is a change of the subsystems' weighting. As a result of the experiments it revealed that the optimal value of the distance parameter $\hat{d}_i$ varies for each target system.

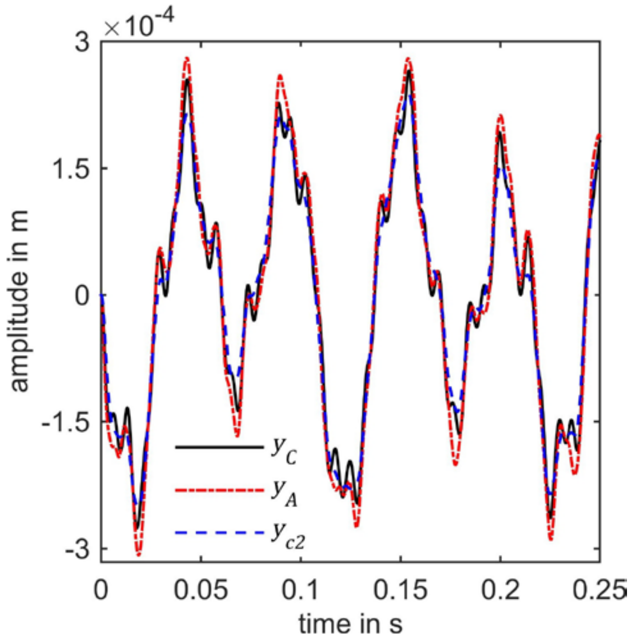

Figure 5 – Comparison of signals (time frame 1)

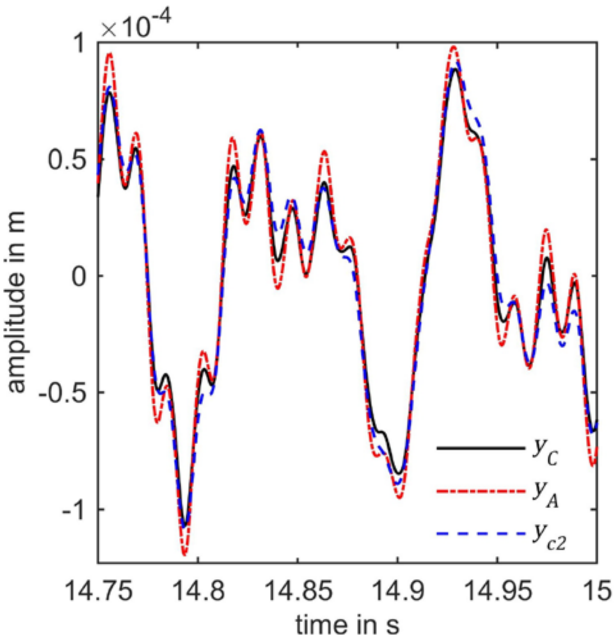

Figure 6 – Comparison of signals (time frame 2)

Furthermore, the figures 5 and 6 visualize the comparison of the best implementation of TSSD, i. e. the one from table 1 with the least RMS value (output y_{c2} with $\hat{d}_C = 101\,\mathrm{mm}$) and the best reference system (output y_A) derived from the extracted modal parameters with respect to the desired system (output y_C). Figure 5 shows the time response of the three systems immediately after the hammer impact and figure 6 illustrates the behavior after $14.75\,\mathrm{s}$. Both plots visualize and confirm the results in table 1. Although the TSSD output y_{c2} does not match the desired signal y_C perfectly, it states a better approximation than the nearest point results y_A, reducing the RMS error by about 26 % for the short time interval and by about 16 % for the long time interval.

5 CONCLUSIONS

Within this contribution a novel approach on the modelling of structural dynamics has been presented. The proposed method requires predefined points and their dynamic behavior in modal representation, which shape the required subsystems. In order to allow a blending between the subsystems a Takagi Sugeno fuzzy system has been utilized. This allows an approximation of the dynamics between the analyzed points, providing the behavior of not explicitly examined areas of the test object. The regulation of this interpolation is user-defined. To secure a correct implementation five requirements for the interpolation were specified. Furthermore, we presented two possible realization options and benchmarked them by an experimental setup. The results show the potential of the proposed approach and validate the introduced theory.

6 ACKNOWLEDGMENTS

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8 BIOGRAPHY

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Using Material Flow Simulation for Improving Energy Flexibility in Combined Coal Mining and Power Plant Operations

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Abstract
Energy efficiency in production is becoming a decisive competitive factor for many companies. The prime reasons are the increasing scarcity of fossil resources and the progressing climate change, both of which gave rise to a multitude of approaches to maximise the use of renewable energy sources (RES). Accordingly, the share of RES in gross electricity generation has grown steadily in recent years. At the same time, a large share of Europe's electricity is still generated in lignite-fired power plants (LFPP). These are supplied by energy intensive open-pit mining (OPM) operations. Potentials to increase the energy efficiency in electricity generation and mining processes are nearly exhausted due to technical and physical limits. This paper presents preliminarily examinations regarding the exploitation of flexibilities under the premise of fluctuating energy supplies and prices by controlling LFPP and OPM in an integrated energy system. The study is carried out using a discrete event simulation model of an OPM.

Keywords
Open-pit mining, Energy efficiency and flexibility, Discrete event simulation (DES)

1 INTRODUCTION

Increased reliance on renewable energy sources (RES) and increased energy efficiency are principal demands of the European legislative. Hence, the share of RES on the gross electricity generation is steadily rising, which makes it a dominant factor in the market. Nonetheless, the share of lignite as a primary energy source is $^{1}/_{10}{}^{th}$ for the EU 27 (total generation ≈ 3.3 PWh), $^{1}/_{4}{}^{th}$ for Germany and $^{1}/_{2}$ for Greece [1]. This underlines the importance of lignite-fired power plants (LFPP) as a reliable, conventional energy source in times with little RES availability. However, their dependence on energy intensive open-pit mining (OPM) operations is becoming an issue for operators. Incremental improvements have pushed the equipment to the point where further efficiency potentials are restricted by physical and technical limits. Consequently, the interactions of individual elements in the LFPP-OPM-system need to be analysed to identify exploitable flexibilities.

Vattenfall already implemented numerous measures to increase the flexibility in the production and the load management of their operations [2]. This work serves as a basis for further analysis on the process structures and energy utilisation in an OPM.

This paper presents an approach based on discrete event simulation (DES) aimed at identifying and assessing the potential for exploitable flexibilities in an OPM. Mining operations act as both consumers and parts of suppliers in the energy system. Hence, a time-based optimisation of energy intensities was expected to improve the overall system behaviour. This could serve to lower costs, improve the process quality and allow for more precise control over increasingly flexible production processes.

The use of DES allowed for the analysis of the complex dynamics of an OPM including stochastic processes. Thus, the effects of competing flexibilities and influences (e.g. energy procurement, personnel deployment, Just-in-Time coal delivery, weather risks, breakdowns, service) could be assessed and measures for controlling these determined. While simulation has been used for similar studies [3][4], the work presented here regards the flows of energy alongside the flows of material. Potentials for improvements were sought by means of a "cross-learning" approach. To this end, the OPM was likened to a timed production system – made up from discrete production and continuous logistics equipment, like an automobile plant. This was believed to be viable, as approaches for improving the production and energy efficiency in such systems by means of organisational measures were subject of prior research (e.g. [5][6]).

The simulation model itself was built using Siemens Tecnomatix Plant Simulation along with the self-developed enhancement module eniBRIC [5]. The latter is a generic tool which can be applied across industries to model both energy consumers and suppliers. Thus, the flows of energy and process media and their interaction with the production processes can be investigated.

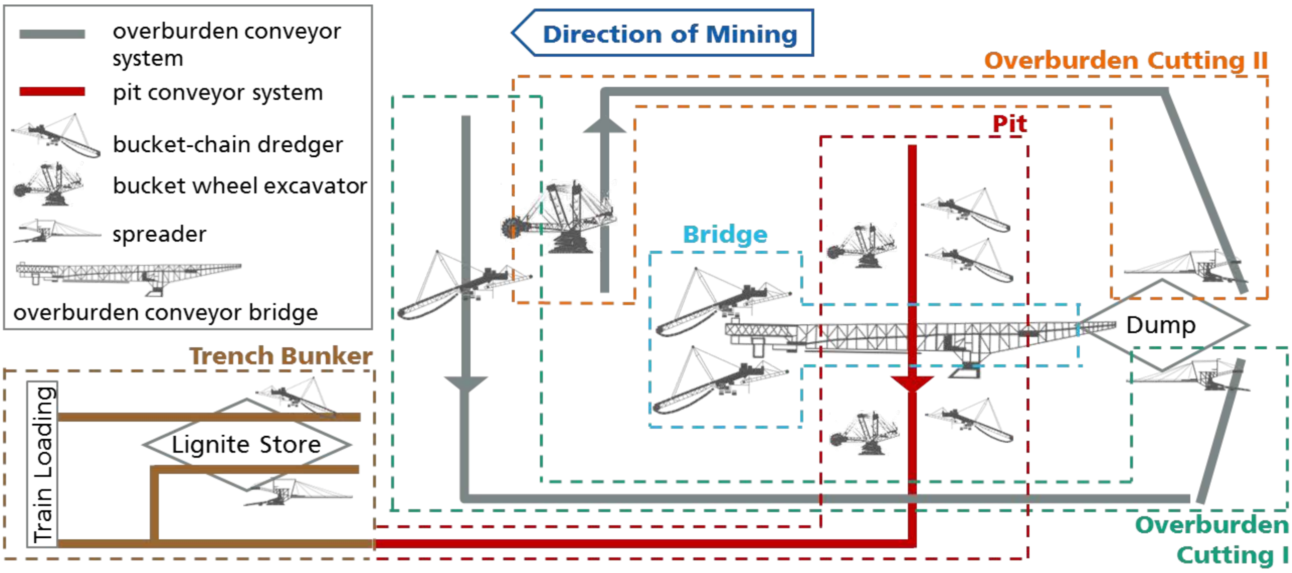

Figure 1 – Layout and production process of Welzow-Süd open-pit mine.

2 CHARACTERISATION OF THE SYSTEM

The OPM investigated in this study is Welzow-Süd in Brandenburg, Germany. In order to illustrate the complexity of the simulated system, the following sections detail the process elements and structures as well as the flows of material and energy.

2.1 Open-pit mining process

The Welzow-Süd OPM is characterised by its continuous equipment technology. Within the OPM, overburden (i.e. layers of earth above the lignite) as well as lignite are removed, loaded onto conveyors, transported and dumped in either the excavation or the trench bunker for later loading, respectively [7]. The ratio between moved overburden volume (m^3) and extracted lignite weight (t) is 6:1. Hence, a year's worth of production is equivalent to 110 Mm^3 overburden and 20 Mt of lignite.

One particularity of Welzow-Süd is the direct dump system used for the overburden (see Figure 1). It makes use of an overburden conveyor bridge, which transports removed material right over the pit to a dump area. The latter is situated on the opposite side of the pit, where lignite has already been excavated. This particular bridge setup is highly performant and is associated with low specific production costs. Accordingly, a primary operation strategy is the maximised use of the bridge group, consisting of two bucket-chain dredgers and the overburden conveyor bridge. In advance of this group, the overburden cutting groups I and II work to remove any additional material in two steps. They each consist of a bucket chain dredger or a bucket wheel excavator, a chain of conveyers and a spreader responsible for dumping overburden.

Below the bridge, the actual lignite is extracted in the pit. For this purpose, two bucket wheel excavators and three bucket-chain dredgers are operated selectively according to the quality of coal which can be produced from the ground. All of them feed onto a single chain of conveyor belts, which is why they can only work concurrently, if they can extract lignite of the same quality. The conveyor belts transport the raw material either immediately to the train loading area or to a coal store in the trench bunker.

In the latter, lignite is dumped on heaps according to their quality. The total capacity is approximately 170.000 t. All lignite is transported to the power station via train from the trench bunker. During the weekend, trains are only loaded from the lignite store and never immediately from the pit. The store is also used when not enough material can be provided from the excavation site to prevent shortages. A minimum of 90.000 t is always kept in store.

The production areas (i.e. groups of equipment) can be regarded as independent production lines, as they are, for the most part, operated individually. In fact, there are also differences between their respective shift schedules. Nonetheless, there are some restrictions between the areas during their operation. For instance, all lignite ordered from the power station needs to be freed from overburden by the bridge group. Similarly, the overburden cutting groups I and II need to maintain a predefined lead on following production areas (opposite to the direction of mining, see Figure 1). Using these lead areas as a source for additional flexibility is – as of now – not intended because the current priority is to maximise the operating time in order to compensate for possible losses from future interruptions of production.

Considering the utilisation statistics of the dredger and the excavators in the overburden cutting groups, up to 20 % of the overall production time is made up of unplanned stops. Hence, short-term-oriented measures are expected to improve the energy efficiency during operation of the system. Similar shutdown concepts, which have been investigated for car body shops (e.g. [8][9]), can potentially be transferred to OPM for this purpose.

2.2 Energy usage

Welzow-Süd's yearly energy consumption is usually between 300 to 350 GWh. Around 50 % of this is used by the overburden cutting (OC) areas, another 30 % by the bridge group and the remaining 20 % by the pit, the trench bunker and other indirect areas, such as the surface drainage. Table 1 shows a breakdown of these figures for selected system elements. All figures refer to average hourly consumptions for actively producing equipment, i.e. no baseload during times when no production commences have been disregarded.

Elements (selection)	Ø-electricity consumption [MWh]
Bucket wheel excavator (OC II)	3.7
Overburden conveyor (OC II)	13.77
Spreader (OC II)	2.71
Bucket-chain dredger	4.31
Overburden conveyer bridge	8.04
Bucket wheel excavator (pit)	0.9

Table 1 - Hourly electricity consumption.

The energy consumption of an OPM operation does not solely depend on the operating time of the system elements but also significantly on the production environment. Especially the geology of the production site has a major influence on the intensity of the material flows and the energy consumption. More particularly, the humidity of the removed material, for instance, can vary which has a direct effect on the transport properties and makes adjustments to the process parameters a necessity. A change of the conveying speed could be the corrective action and would translate into lower or higher energy consumption and higher or lower flow intensity, respectively. Similar correlations exist for other equipment of the OPM.

Provided the conveying speed remains unchanged, the actual energy demand of the conveyer belt depends on the currently transported mass. This causes variable load profiles when the belt is initially filled during start up or emptied during shut down. It also causes some variability if the transported material is less homogeneous. Furthermore, the energy demand of the conveyer belts is very dependent on the length and gradients which have to be covered. For example, the belts in the overburden cutting areas can be as long as 14 km and those spanning from the pit to the trench bunker may have to climb up to 80 m in height.

Lignite OPMs basically fulfil two roles in the energy system. On the one hand, they are a supplier to the power station and thus to energy generation in general. On the other hand, they are a customer, procuring electricity from the grid. In order to improve the systemic energy efficiency from the point of view of an operator, both roles have to be taken into account. Hence, the energy consumption in OPM operations was identified as a viable source of flexibility for the grid. The simulation-based study was, thus, selected to improve the understanding of existing levers in the processes, to identify exploitable flexibilities and assess the significance of existing interdependencies within the system.

3 SIMULATION STUDY

To examine existing flexibilities and potentials for optimisation, the considered OPM system was modelled in preparation of subsequent simulations. This is detailed in the following subsections.

3.1 Preparation

Prior to the actual modelling the system boundaries needed to be defined. It was determined that only system elements which are directly related to the material flows of lignite and overburden as well as the flow of electric energy among these were to be considered. Other indirect areas of the OPM (e.g. water management, operation of auxiliary devices or recultivation) were disregarded. The train loading specified as the outer boundary of the system. The LFPP acts merely as an in-company client which initiates production orders. Furthermore, the different soil types found in the OPM were reduced to the three essential ones, which are further characterised according to their respective composition. With respect to their quality, three types of lignite were considered. This abstraction of the OPM was the starting point for the modelling of manufacturing equipment and production processes.

Based on extensive actual data, an analysis of the temporal processes and the associated energy demands was carried out. Thus, an actual status of the OPM could be ascertained. This data was acquired from different sources and had varying resolutions and units of measurement. In addition, the data availability differed for individual system elements. Accordingly, the in-depth analysis required pre-processing to attain comparable data quality. The emphasis of the data analysis was put on the identification of the operating states and the assignment of the corresponding energy demands as well as the description of the correlations between output and power consumption.

High resolution modelling of the geological profile was determined to require inexpedient effort. Hence, the geological profile was abstracted by means of a time series of volume units which represents the material removed from the ground. For this purpose, measurements of the production output and the electricity consumption were used to define volume packages, which comprise five minutes' worth of operation. The result is a series of material removed from the ground for each excavator

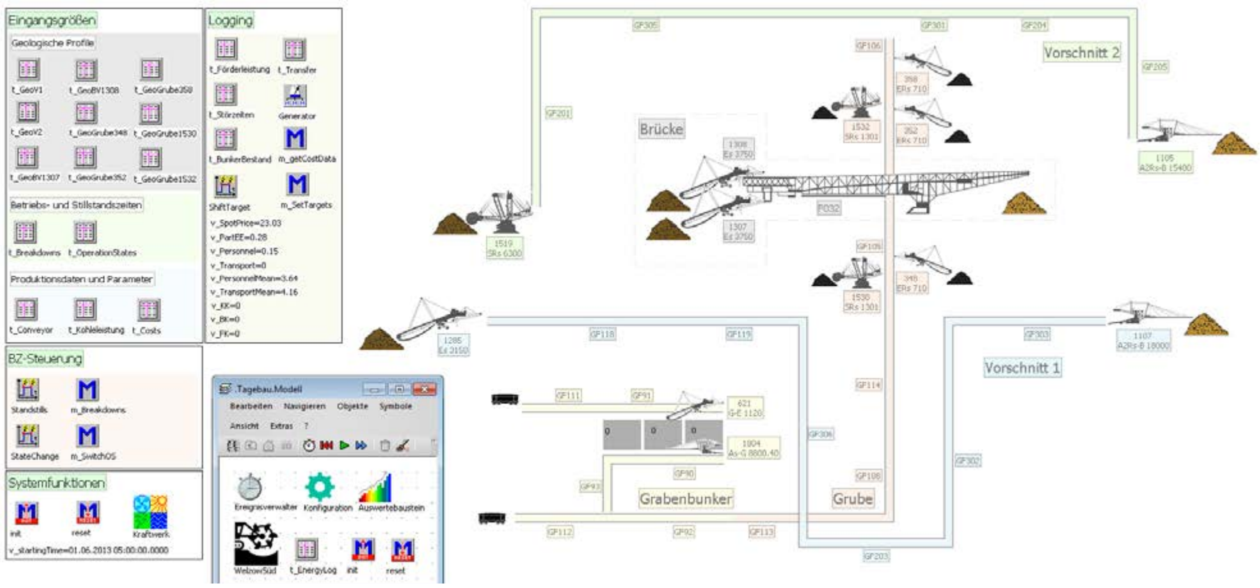

Figure 2 - Screenshot of the simulation model.

3.2 Modelling

To enhance the process understanding of the increasingly flexible OPM, all operating areas were modelled in a single sub model. Its layout was recreated in the likeness of the real of the OPM but the deposits were not visualised (see Figure 2).

The volume packages, which make up the geological profiles, were modelled as classes of movable units, one for each type of soil or coal. These were attributed with respective volumes, power demands, energy costs, cycle times etc. During simulation, source elements create instances of these classes (MUs) in the order of the predefined series for the operation area and feed them into the system.

All excavators were modelled on the basis of a single object class, so they share the internal structure as well as the functionality. Differences were made in terms of the energy flows parameterised in the corresponding eniBRIC instances (see section 3.3). During simulation runs, excavators receive five minutes volume packages, split them and generate new smaller packages (representing approximately 30 seconds' worth of production).

The functionality of the overburden conveyor bridge, the conveyor systems and the spreaders were modelled identically as conveyor lines. Their volume-dependent energy consumption is calculated by means of pre-determined regression curves, which map the current material volume on the element to an energy demand. The parameters of the eniBRIC instances are updated as soon as the content changes to recreate the correct load profile.

At the beginning of the simulation necessary input data (e.g. non-operating periods, spot market prices, lignite demand as well as cost rates for personnel and transport) was read from external files. Breakdowns and changes of equipment operating states were automatically triggered and controlled through custom methods (scripted procedures). The processes in pit and trench bunker were controlled similarly on the basis of the requested lignite.

3.3 Integration eniBRIC

Energy flows in the system were modelled using the generic module eniBRIC [5]. It was instantiated in each element of the simulation model which was considered energetically and associated with the respective controlling logic of the material flow elements. The previously identified operating states along with the appropriate energy demands were configured in the corresponding parameter tables. Further entries were made to determine, which operating states would allow for material flow/production in the simulation elements.

The infrastructure for electricity – the only energy source considered – was modelled using the pre-defined supplier module from the eniBRIC library. Moreover, the configuration and evaluation modules were instantiated. The earlier was used to setup the associations between the energy consuming and energy supplying elements and other necessary settings. The latter provided capability for ad-hoc-visualisation as well as various other evaluations concerning the energy consumption.

3.4 Validation

In order to identify and verify the effectiveness of new operational strategies for the OPM, which make use of flexibilities in the system, the simulation model needed to be validated. In particular, the system output and its energy consumption were of prime importance to ensure that simulation results matched reality with a tolerable margin of error.

The validation was completed using real measured data of an entire month. Data generated by the simulation model was collected and compared against the former. An iterative process was then performed to tweak the model where necessary, to

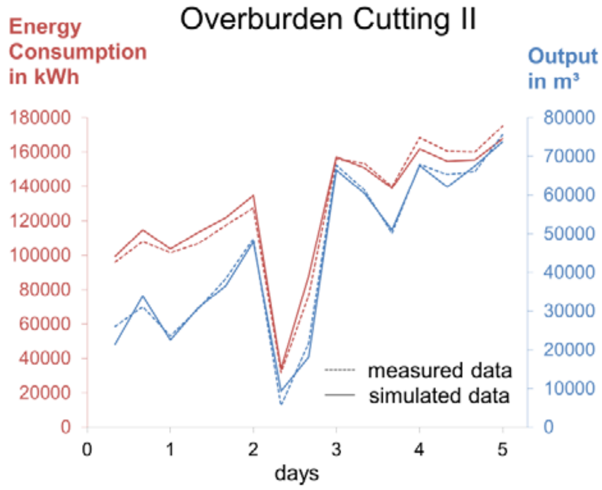

Figure 3 - Comparison of energy consumption [kWh] and output [m³] for overburden cutting II.

improve the correspondence of its behaviour with that of the real system.

Figure 3 shows an exemplary comparison of the two data series for the overburden cutting II production area. In summary, the final examination of all measured and simulated data revealed that the model generates valid data.

4 SIMULATION EXPERIMENTS AND RESULTS

Following the model creation and validation, the model was used for simulation experiments directed at the identification of flexibilities. For this purpose, various indicators were defined to assess the results. Examples are:

- Electricity price variance from the average price,
- Primary energy factor for German electricity mix,
- Target/actual deviation of lignite output,
- Utilisation of capacity of lignite production, and
- Cost variance for personnel and transportation.

These indicators allow for, inter alia, the investigations of flexibilities in the electricity market or changes in the lignite demand. The required information for these indicators originated from both real data and simulation data. Thus, the simulation model enhanced with the indicator evaluation could be used to determine, which production processes are deemed influenceable, what the scope of action would be and what effects are to be anticipated.

Besides time series of the predefined indicators, the simulation can be used to calculate data which otherwise cannot be determined in the real production system. This particularly concerns the following specific indicators for each volume package:

- specific power consumption,
- specific production time,
- specific lead time,
- specific personnel and transport costs,
- specific energy costs, and
- specific contribution to overall system efficiency.

Since the power demand of the system elements is volume-dependent and calculated using different regression curves, the energy consumption for each volume package was constantly updated until the package left the system. Spot market prices and the percentage of renewable energies were also considered subjects to temporal changes. Hence, the specific energy costs had to be updated continuously. The contribution of demand management to the overall system efficiency can be measured on the data of the energy system´s share of renewables at each time slot.

The potentials of selected flexibilities were initially analysed qualitatively and quantitatively in “what-if-experiments”. The variation of parameters and input data was based on the expertise provided by Vattenfall. First experiments included several simulation runs, during which, for example, the lignite demand was reduced in an “unplanned demand reduction scenario” by 30 % compared to the reference scenario, or an altered electricity price curve was supposed. The earlier showed that the trench bunker was gradually filling up to its capacity because the production in the overburden areas and the pit was continuing regardless. In the future, the detailed results will be analysed to determine if and how the process control can be optimised to prevent excessive stocking of lignite. Altered electricity prices, on the other hand, naturally caused a change in the imputed costs for the production. The results of this simulation variant can be analysed to devise more cost efficient processes. It further serves as a basis to be able to predict actual production costs in advance.

The preliminary experiments are currently being scrutinised by Vattenfall’s mining experts for implications on the operation of OPM and identified flexibilities, in particular. Additional experiments are planned for the future.

5 CONCLUSIONS

This article introduced an approach which makes use of discrete event simulation to identify “cross-learning” potentials by likening a lignite open-pit mining (OPM) operation to a discrete production system. The energy flows in the simulation were modelled using the eniBRIC module, which is applicable across sectors. The simultaneous consideration of material and energy flows in the same simulation tool offered by eniBRIC allows for the investigation of opportunities to increase the systematic energy efficiency in production systems.

Consequently, the OPM Welzow-Süd was modelled, parameterised and validated using Siemens Tecnomatix Plant Simulation to identify and asses potentials arising from the targeted exploitation of flexibilities. Using this model, the impact of dynamic basic conditions – such as electricity supply and price, lignite demand and weather – on the production could be included in the considerations. Thus, the experiment-assisted development of new optimised operation strategies became possible. Preliminary experiments have already been completed and are currently being analysed by mining experts. Based on the knowledge gained from these, the next step requires the creation of a more elaborate design of experiments and its execution as well as analysis of the results.

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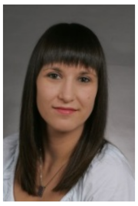

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Modelling Productive and Ergonomic Work Processes – Introduction of "Human Work Design"

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Abstract
Already today, the modelling (description and evaluation) of productive and ergonomic work processes or work methods plays a significant role, for example with respect to the design paradigm "Industry 4.0" for production work. It is going to gain even more significance for the design of human work – in the sense of planning, implementing, and improving, for example, man-machine-interaction, man-robot-collaboration and man-computer-interaction. In the newly developed "Human Work Design" (HWD) the description of work processes gains center stage in the design of human work – as in Gilbreth's time. This results in transparency, and a new and unique approach to the design of work processes. The new process building block systems MTM-HWD® describes movements of people in conjunction with an ergonomic assessment procedures (e. g. EAWS - Ergonomic Assessment Worksheet) in one step. Thus, for the first time will allow a direct correlation in designing productive and ergonomic work processes (work methods).

Keywords
Human Work Design, Ergonomic Assessment, Modelling Human Work

1 INTRODUCTION

Already today, the modelling (description and evaluation) of productive and ergonomic work processes or work methods plays a significant role, for example with respect to the design paradigm "Industry 4.0" for production work. It is going to gain even more significance for the design of human work – in the sense of planning, implementing, and improving, for example, man-machine-interaction, man-robot-collaboration and man-computer-interaction [1].

The key to this gain in significance lies in the fact that already today many companies describe and evaluate their work processes in digital form (e. g. with TiCon). These data are, thus, available for use in manifold other software tools (e. g. for the creation of routings), in the Digital Factory, or in cyber-phyiscal systems. The digitalization and interlinking of different methods (e. g. MTM Methods-Time Measurement, EAWS Ergonomic Assessment Worksheet) and software tools (e. g. MTMergonomics®) opens up new possibilities for the preventive and consistent design of productive and safe processes.

With his motion studies and the development of the Therbligs (1924), Gilbreth set the basis for modelling human work. The Therbligs enabled him to describe and subsequently design the motions performed by the worker [2]. Merely describing work processes in this form was sufficient to design ("good") work processes. For this, no time-related evaluation, i. e. time values for the Therbligs, was necessary, or did exist.

The building block system MTM-1 (the MTM Basic System) was developed in 1948. It was based, among others, on the Therbligs. It describes human work processes by means of defined process building blocks and evaluates them on the basis of standard time values, which are immanent in the process building blocks. Thus, by using MTM process building block systems, models are "automatically" produced, i. e. target results are directly determined. This fact represents one of four dimensions that define the singularity of the MTM method: model building as an integral part of the method [3].

An essential aspect in the design of human work is the calculation of target times. Due to MTM process building blocks this is possible already before the work system has been set up, i. e. at a very early planning phase.

During the first decades that followed the development of MTM, companies (mostly) focused on the calculation of target times. The importance of describing the work process and, thus, the work method itself, which ultimately defines the time required, evermore faded into the background.

In the following years and with the focus clearly on time data determination, a number of higher aggregated building block systems were developed from the MTM basic system (MTM-1): MTM-2, MTM-UAS (Universal Analyzing System), MTM-MEK (MTM for One-of-a-Kind and Small Batch Production). In 1978, MTM-UAS and MTM-MEK were developed to increase the application speed of the building block system for planning and designing longer-cycle and more diverse work processes [3]. In contrast to MTM-1, the building block systems MTM-UAS and MTM-MEK no longer describe the actual work process in chronological order, but solely the general conditions under which it is being performed (e. g. accuracy of Place, Distance Classes). This is due to the type of building block aggregation (e. g. elimination of influencing factors) – in other words: due to the design principle of the building block systems.

With the revival of Industrial Engineering [4], [5], [6] from the early- to the mid-2000s, the brand MTM, with its various process building block systems and other MTM methods, such as ProKon (Production-Oriented Design) or EAWS [7], has made substantial progress. At the same time, the MTM application has been significantly extended to support all aspects along the process chain. The development of MTM, of its understanding, perception, and importance – away from being a mere predetermined motion time system (PMTS) – into a process language is best proven by the fact that MTM, as a basic method, has been considered an integral part of Industrial Engineering since the publication of the handbook “Industrial Engineering – Produktivitätsmanagement mit MTM” (“Industrial Engineering – Productivity Management with MTM”) in 2012 [3].

2 PRACTICAL INNOVATION

The modelling of work processes or work methods not only supports the design of work systems. It also helps to find answers to further questions and is used for evaluation purposes, for example in quality assurance or eHPV (engineered hours per vehicle). In this connection it became obvious that the existing MTM process building blocks yield only part of the required information. Hence it appeared necessary to increase the proportion of information contained in the individual MTM process building blocks to enable a broader application, for example in evaluating and reducing ergonomic risks.

The development of new building blocks with more inherent information represents a new approach or principle in the development of process building blocks, as it is in contrast to the traditional building block aggregation (creation), where influencing factors were reduced. The influencing factors in MTM-HWD® (e. g. trunk rotation, distance class) are clearly defined and are scaled by using pictograms (cf. figure 1).

During a two-year development phase a new building block system was developed – MTM-HWD® (Human Work Design). This is the first building block system to allow for the definition of a work process description that yields information on both time AND ergonomics. This allows for simultaneous determination of the basic time and physical hazards (the latter by using EAWS). The HWD® actions (OBTAIN, DEPOSIT, RETRACT, APPLY PRESSURE, MOVE LEG und CHECK) not only describe human motions; the system also allows for the first time to describe the postures adopted during the process. For this, new process building blocks were created (e. g. HOLD, WAIT). In doing so, the developers deliberately decided not to assign process building blocks to the HWD® actions, to make the descriptions available to the untrained user also [8].

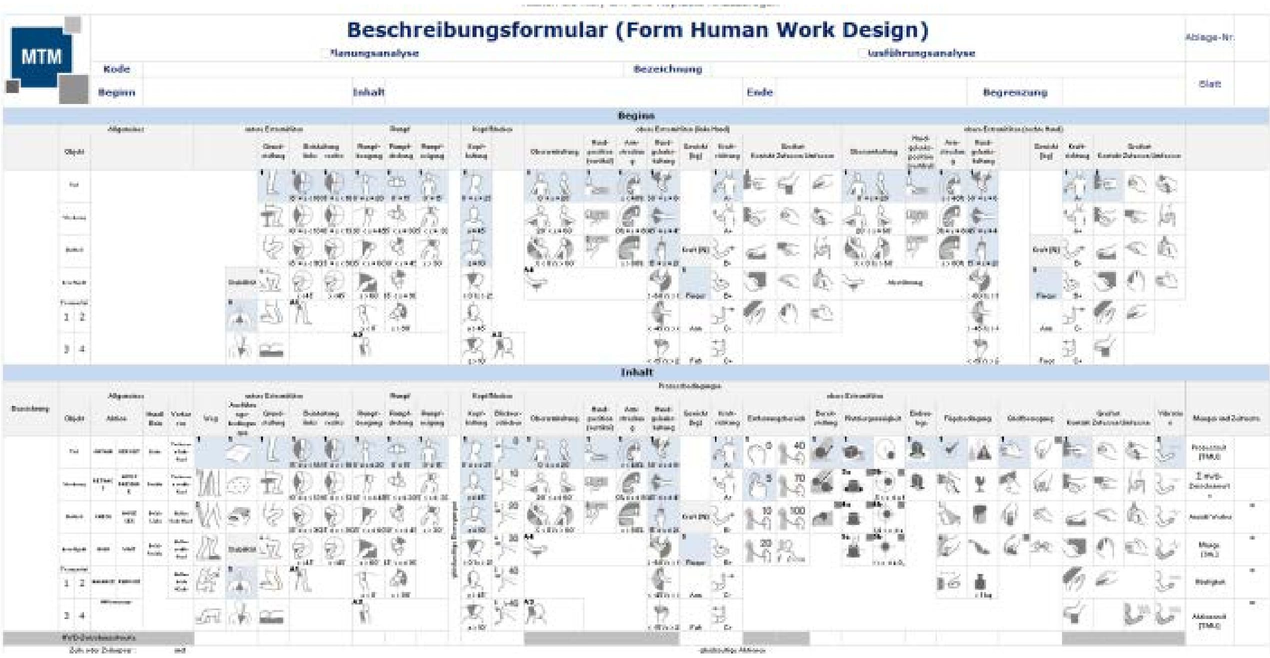


Figure 1 - Description form of the building block system Human Work Design (MTM-HWD®).

2.1 Describing human work with the building block system MTM-HWD®

The multitude of influencing factors that have to be considered while creating aggregated building blocks, i. e. combining basic motions and influencing factors according to defined principles resulted in a new appearance. Whereas the classical MTM application is characterized by the use of a data card and the filling-in of structured analyzing forms, in MTM-HWD® a description form is used in which the corresponding actions together with their influencing factors have to be marked with a cross. To increase the application (i. e. the checking of the corresponding boxes) speed a highlighted basic value was defined, which needs not to be marked. This value supports the user in designing productive and ergonomic work processes. Thus, MTM-HWD® enables the creation of a motion model of human work. MTM-HWD® always describes the complete motion. Therefore, a partial description (of, for example, only the time-related influencing factors) is not possible. Apart from that, further influencing factors were added (e. g. head posture) that are not considered in the other existing systems. The intention was to develop a building block system with the help of which an anthropological motion model can be created. That means that the description not only yields more information than is required for one parameter (e. g. time); in fact, it comprehensively describes the individual body parts, such as lower limbs, trunk, head / neck, and upper limbs.

2.2 Assessing human work with the building block system MTM-HWD®

Assessment is performed in two steps. In step one the individual HWD® influencing factors are assigned standard times from which, based on a (company-specific) time structure, target times can be derived. In step two a load analysis is performed by coupling an ergonomic assessment method (e. g. EAWS) to the HWD® description, in order to determine a load index (score value). In other words, the information from the description (such as actions, influencing factors, times, frequencies) is made available to the algorithm (sections and rules) of the assessment method.

3 SCIENTIFIC VALIDATION

3.1 Study on coupling ergonomics and the building block system MTM-HWD®

The appropriateness of the HWD® description as basis for an ergonomic assessment was scientifically proven by the Institute for Ergonomics and Human Factors of TU Darmstadt. In doing so, the IAD checked that MTM-HWD® provides a suitable and complete description for the ergonomic assessment tools APSA [9], EAB [10], and EAWS [7].

As APSA and EAB are derivatives of EAWS or its predecessor AAWS [11], the common features of, as well as, the differences between these tools were first analyzed. Based on this, the relation of EAWS to the iteratively developed building block system MTM-HWD® was established. Then the peculiarities of the other two tools were examined. The examination of MTM-HWD® in relation to EAWS was based on the line-by-line structure of EAWS, by assigning each of the 26 HWD® influencing factors to the corresponding load features of the assessment tool (figure 2).

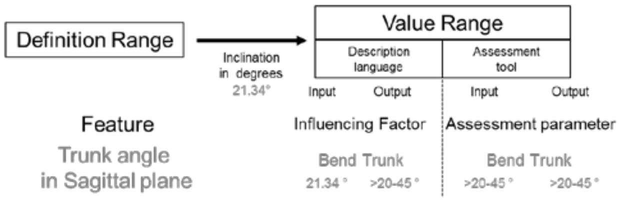


Figure 2 - Terminology related to the scientific examination of the building block system MTM-HWD®.

It was checked whether the building block system MTM-HWD® and its influencing factors, which are used in the load analysis (e. g. trunk angle in sagittal plane), are dissolved to such a degree that the information is made available in the appropriate accuracy for the analyzed assessment tools. To evaluate the completeness of the description language, the scaling of every single influencing factor was analyzed and the representation of the maximum value range of the individual feature considered (definition range) (figure 3).

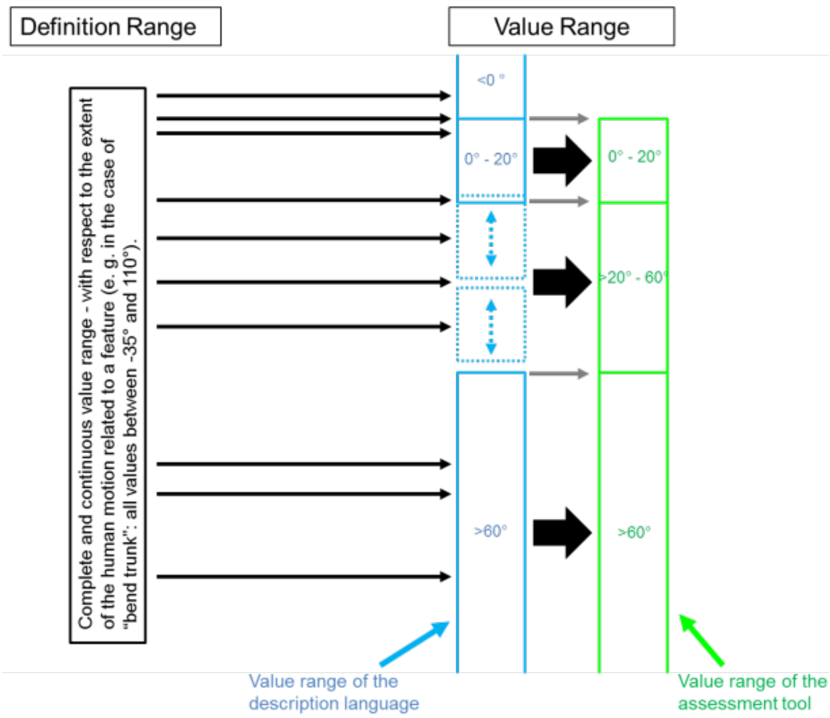


Figure 3 - Systematic analysis of the representation of continuous parameters in the description language, taking "Bend Trunk" as an example.

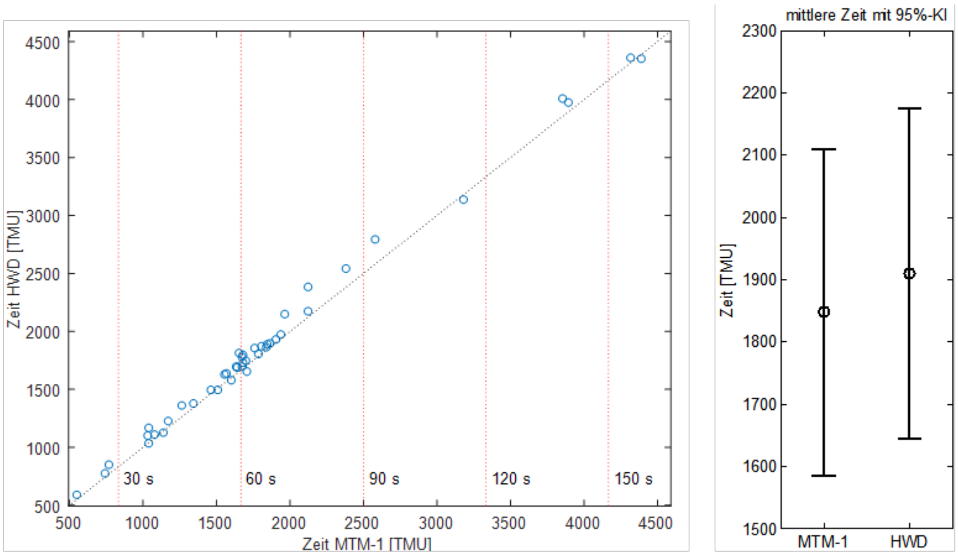
It was also checked whether the value ranges described with MTM-HWD® are ultimately complete, clear, and unambiguous. During the development of MTM-HWD® future advancements of the ergonomic assessment tools were also considered. For example, the feature "Head Posture" is innovative for future ergonomic assessment tools.

In addition, every influencing factor in MTM-HWD® avails of a basic value that represents ideal process conditions for ergonomics, required energy, time, and/or application speed. This basic value has been preselected in the description forms. So, while describing an ideal process, the time required for entry is reduced to a minimum. An increased number of deviations from these basic values helps the user (e. g. a process planner) to identify improvement potentials in the motion process. This approach supports the MTM motto (First time right!) The examination by the IAD justified and proved the selection of every basic value [8].

3.2 Study to verify the building block system MTM-HWD®

To be able to assess the validity of the new building block system, the Institute of Industrial Engineering and Ergonomics of RWTH Aachen (IAW) in a first step performed statistical studies (verification). An excerpt of these studies is presented below. First, 43 data sets of a sample description were analyzed with respect to the frequencies of the used MTM-1 and HWD® process building blocks. The MTM-1 building blocks most frequently used in the observed data sets were: Move (27.3 %), Grasp (18.7 %), Reach (15.6 %) and Release (13.0 %). In the MTM-HWD® analyses of these data sets the most frequently used building blocks were: Deposit (60.6 %) and Obtain (31.1 %). The next step of the analysis consisted in comparing the gathered total times of the HWD® work cycles with the total times of the MTM-1 analyses. When the data sets were analyzed with the higher aggregated building block system MTM-HWD® (figure 4) the result was an average of 1909.4 TMU (standard deviation: 887.2 TMU) – higher than the data received by the analysis with MTM-1 (arithmetic average: 1847.6 TMU; standard deviation: 879.8 TMU) [8].

By means of a t-test (α=0.05) it could also be verified that there definitely is a difference between MTM-1 and MTM-HWD® [$t(42)=-6{,}0794$; $p<0.001$]. The times gained with MTM-HWD® exceed the MTM-1 times by an average of 61.8 TMU, the 95th confidential interval being (41.9 TMU; 81.7 TMU). The results are shown in figure 4.



(a) (b)

Figure 4 - Comparison of MTM-HWD® and MTM-1 time values, represented in a scatter plot (a) and by the corresponding 65th confidence interval (b).

The study of the intended application range yielded an average deviation of MTM-1 times from the MTM-HWD® times of less than 5 %.

All in all, the performed analyses have shown that there is a significant difference between the building block systems MTM-1 and MTM-HWD®. The final result of the verification was not yet available at the time of publication [12].

Human Work Design revolutionizes the modelling of human work processes. The previously individual steps of collecting information for the description of work process or work method, of evaluating the time, and of evaluating physical loads are now performed in one go. For this, a new notation, based on pictograms and (aggregated) MTM-1 process building blocks, was developed for the description of work processes. By this, time-relevant influencing factors of the work method (such as distance classes, cases of Grasp, accuracy of Place, weights), as well as, ergonomic influencing factors of the ergonomic assessment (such as rotate trunk, bend trunk, posture, arm's reach, weight, force, finger forces, case of Grasp, positions of hand, arm, and shoulder joints) have been interlinked and represented or summarized in a new MTM process building block system.

4 FINDINGS

In the newly developed "Human Work Design" the description of work processes gains center stage in the design of human work – as in Gilbreth's time. In addition, it integrates time, reflected in the duration of the work process, as an immanent result of the modelling of work processes.

This results in transparency, and a new and unique approach to the design of work processes. Due to pictograms it also enables interdisciplinary understanding for planning and designing of human work, and at any point of time along the process chain at that.

With the help of the HWD® actions (HWD® process building blocks) and the related HWD® process conditions (HWD® influencing factors) the work process (man's motions and postures) is profoundly modelled. The immanent result of this modelling comprises the work method itself, a basic time, and also an ergonomic assessment (points), provided by an ergonomic assessment technique (e. g. EAWS). In addition, the use of pictograms instead of the so far common coding (e. g. R20A in MTM-1) in the MTM process building block systems, enables an easier and better understanding of the work process description. As a result, even persons who are not MTM-trained are able to understand the process description.

MTM-HWD® represents the change in understanding, perceiving, and applying MTM towards an international process language for modelling human work. Hence, this article features, on the one hand, the evolution of the MTM method for describing and evaluating productive and ergonomic work processes. On the other hand, it demonstrates the principles, the development, and the functionality of Human Work Design, and specifies the new MTM process building block system by means of a practical example.

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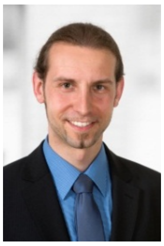

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A Standardized Value Stream Management Method for Supply Chain Networks

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Abstract

In a globalized market environment, almost all companies operate in complex supply chain networks. A high degree of product diversification in combination with rapidly changing customer needs require cross-enterprise supply chain collaboration, which causes communication problems. A way to cope with this complexity is to optimize both internal as well as external processes in a holistic manner and to define standards for interaction, collaboration and communication procedures. An established method for process analysis and optimization is Value Stream Management (VSM). Despite a variety of promising VSM approaches, there is a lack of a standardized VSM method, especially with regard to complex supply chain networks. Thus, a review of methods for process visualization and their suitability for different process types shall be discussed. A common VSM method with integrated features according to the specific needs of the applying organization will help to optimize the value creation in cross-enterprise supply chains.

Keywords

Lean Manufacturing, Value Stream Management, Supply Chain Networks

1 INTRODUCTION

Due to rapidly changing market conditions in a globalized environment, numerous companies strive for international competitiveness, e.g. by shifting operations to emerging markets [1]. One goal of these globally operating companies is to achieve integrated product and information flows based on robust IT infrastructures, which enable efficient collaboration and communication procedures between suppliers and customers. However, cross-enterprise supply chain networks in combination with a heterogeneous and inconsistent VSM landscape lead to waste like repetitive work, e.g. during auditing processes. Thus, a standardized and comprehensive VSM method will enhance the analysis of complex supply chain networks.

According to Aitken, a supply chain is defined as "a network of connected and interdependent organizations mutually and co-operatively working together to control, manage and improve the flow of materials and information from suppliers to end users" [2]. The described cooperation of different companies in supply chain networks requires standardized collaboration and communication procedures, which are investigated thoroughly in the following sections.

This paper is structured as follows: firstly, a general literature review on existing collaboration and communication procedures in supply chain networks is presented. Secondly, selected methods for network and process analysis are discussed, followed by the description of a developed multilevel VSM approach and an associated data acquisition method. Finally, this paper concludes with a critical review of the novel approach and further steps of research in this field.

2 COLLABORATION AND COMMUNICATION IN SUPPLY CHAIN NETWORKS

Cross-company collaboration and communication are essential aspects of complex supply chain networks. In order to better understand the basic principles of supply chain collaboration based on communication procedures in globalized supply chain networks, recent scientific publications in these fields have been investigated.

2.1 Supply Chain Networks

Farahani et.al. [3] present a review on competitive Supply Chain Network Design (SCND) and develop a framework to model those supply chain patterns. SCND describes the structure of supply chains, their cost and performance, e.g. by analyzing the number, size and location of facilities in a supply chain. Based on these analyses, tactical and operational decisions could be taken.

Closed-loop supply chains (CLSCs) have in addition to the forward-oriented chain a reverse chain for recycling purposes. Özceylan et.al. [4] investigate the modeling and optimization with regard to closed-loop supply chain network design and disassembly line balancing. The authors present a nonlinear mixed integer programming formulation for solving strategical and tactical decisions in supply chains.

Another publication in the field of SCND in combination with CLSCs by Devika et.al. [5] deals with the design of a sustainable CLSC network based on a triple bottom line approach incorporating economic, environmental and social impacts. In order to consider further environmental aspects like greenhouse gas emissions, Urata et.al. [6], Comas Martí et.al. [7], Sparks and Badurdeen [8] as well as Eskandarpour et.al. [9] present their approaches to model and balance economic and environmental aspects of global supply chain networks. With the help of different mathematical formulations, e.g. mixed integer programming (MIP) problems, the market correlations are modeled while considering environmental aspects, such as CO_2 emissions within globalized supply chains.

Schuh et.al. [10] develop a concept for the management and the design of production networks. In consideration of the structural complexity as a key parameter of global networks, the authors present an approach for the analysis and optimization of production networks.

Furthermore, Matt et.al. [11], adapt the value stream optimization approach to collaborative company networks in the construction industry. The authors describe a methodology to design an integrated and customized value stream map, which is tested in a collaborative project of applied research.

The described approaches focus mainly on the analysis and optimization of specific supply chain structures or associated process types. However, a common VSM method suited for supply chain networks is not provided. With regard to a wider range of process types, a holistic and standardized VSM approach needs to be developed.

2.2 Supply Chain Collaboration

In order to get deeper insights in supply chain networks, an investigation of general collaboration procedures within supply chains is advantageous.

According to Shephard [12], the term collaboration refers to a "cooperative relationship built on developing synergies within and across company boundaries that help all supply chain partners". The author analyzes the collaborative demand and supply planning between supply chain partners. Benefits of collaboration are presented as well as guidelines for the right choice of supply chain partners. Moreover, different levels of collaboration, such as limited, partial and full collaboration are explained.

To facilitate supply chain collaboration, Schubel et.al. [13] ask for uniform reference models and common definitions of basic terminology in production and logistics. Therefore, the authors analyze reference models in five different fields: Computer Integrated Manufacturing (CIM), Production Planning and Control (PPC), Digital Factory, Supply Chain Management (SCM) as well as in production, logistics and factory planning in general.

Cao and Zhang [14] give a broad overview of collaboration within supply chains. In addition, the importance of IT resources and inter-organizational systems (IOS) is stressed. Different levels of collaboration and their impact on sharing of crucial data among supply chain partners are addressed.

These general approaches of cross-enterprise collaboration in supply chains need to be extended and integrated with regard to the development of a standardized VSM method.

2.3 Communication standards for supply chain networks

In the past decades, different standards for intra- and inter-company communication have been developed. Communication standards that guarantee a secure and efficient Electronic Data Interchange (EDI) are for example "EDIFACT", "GAEB" in the construction sector, "ebXML" in the business sector, "Fortras" in the transport sector or "openTRANS" in the trade sector. In addition, there are other communication standards like "RosettaNet", "Universal Description, Discovery and Integration" (UDDI) or "Web service description language" (WSDL). Most of those standards are based on the "Extensible Markup Language" (XML). In the work of Cecere [15], EDI is described as a workhorse of the value chain. The publication presents deeper insights with regard to the application of EDI in extended supply chains with a special focus on processes for Business-To-Business (B2B) connectivity. The study reveals that an efficient use of EDI leads to meaningful business results, e.g. shorter shipment cycles or a better order fulfilment.

To ensure an efficient collaboration within global supply chain networks, communication standards and procedures have to be followed. These common communication procedures will enhance integrated information flows across company borders and need to be considered while analyzing complex supply chain networks.

3 EXISTING METHODS FOR SUPPLY CHAIN NETWORK AND PROCESS MODELING

The following chapter describes existing methods for supply chain network analysis as well as for process modeling and visualization. Furthermore, the applicability of these methods for cross-enterprise supply chain networks is evaluated.

3.1 Supply Chain Network analysis techniques

One of the first approaches for supply chain network analysis has been developed by Gereffi and Fernandez-Stark [16]. According to them, the following four dimensions of global value chain analysis can be distinguished:

- input-output structure
- geographic scope
- governance
- institutional context

From a governance perspective, Gereffi et.al. [17] have introduced a typology of five different governance patterns, from strong hierarchical structures with a high degree of power asymmetry and explicit coordination to market based structures with a low degree of power asymmetry and explicit coordination.

Ferrarini [18] introduces a method to map global networks with regard to production and trade. To perform the mathematical analysis of the data set, the author defines a "Network Trade Index" (NTI) as a weighted index for the supply of countries. By means of a force-directed algorithm, the global network can be solved and analyzed.

The concept of netchains is introduced by Lazzarini et.al. [19]. Netchain analysis comprises supply chain and network analyses. The study of netchains is the first step to optimize inter-organizational collaboration by analyzing interdependencies between different stakeholders of a supply chain.

The development and application of an "Inter-Country Input-Output" (ICIO) model is described in the OECD report on global value chain mapping [20]. The ICIO model is able to analyze trade and production of countries based on international input-output tables.

The four presented methods for network analysis are all suited for global supply chain analysis and optimization. Nevertheless, the described approaches are based on country level and do not provide a value stream analysis from a company perspective.

3.2 Process modeling and visualization

3.2.1 SCOR model

The Supply Chain Operations Reference model (SCOR) developed by the Supply Chain Council, is the leading reference model for internal and cross-enterprise business processes. The process description is divided into several levels. On the first level, the processes are categorized according to the following structure:

- Plan
- Source
- Make
- Deliver
- Return
- Enable

Besides these categorization and modeling efforts, the SCOR model provides a comprehensive overview on Key Performance Indicators (KPIs), which are suited for the assessment of the supply chain.

3.2.2 Value Stream Mapping

Value Stream Mapping is a key concept and one of the initial steps of Value Stream Management (VSM) to capture relevant process steps and corresponding value stream data. As main literature in the field of VSM, the work of Rother and Shook [21] has to be considered, since it is the first systematic approach to describe and optimize value streams. The resulting VSM method is a concept for the structured modeling and optimization of product and information flows.

Based on the existing approaches in the field of VSM, Womack and Jones [22] develop an extended VSM method by expanding the perspective from a single company to supply chain optimization. By means of this extension, there is the possibility to map product and information flows across company borders.

3.2.3 Further methods for process modeling and visualization

Besides the process modeling techniques described above, there are further methods for process modeling and visualization. The approach "Architecture of Integrated Information Systems" (ARIS) developed by Scheer [23], helps to map processes and associated data flows on company level. Other means for process modeling are for example swimlane diagrams or the "ICAM Definition for Function Modeling" (IDEF0). Several of these methods are based on flow charts, which have their origins in the formulation of "Flow Process Charts" (FPC) by Gilbreth. In addition, there are different approaches to deal with the complexity of value streams in terms of components. Supporting approaches for visualizing multiple value streams in supply chain networks are for example the Critical Path Method (CPM), Value Network Mapping (VNM) or graph theory in general.

The application of the described methods is often well defined within a company, but needs to be extended and standardized for a common modeling and visualization of all types of external processes.

4 MULTILEVEL VSM METHOD FOR SUPPLY CHAIN NETWORKS

In the following chapter, a new VSM method for the analysis and optimization of supply chain networks on company level is presented. Beyond existing approaches of extended VSM, this new method incorporates data acquisition and value stream visualization techniques for differing applications.

4.1 Extended VSM approach for various process types

Complex supply chain networks require well-defined analysis methods to facilitate and optimize cross-enterprise collaboration procedures. In practice, there is often no common understanding of those procedures, especially across company borders. This leads to communication problems, repetitive work and consequently to waste due to a differing use of these techniques. Therefore, the existing methods for process and network analysis have to be extended and standardized.

In contrast to the described value chain analysis approaches on country level, the following VSM method has been specially developed for a multilevel assessment of complex supply chain networks on company level. The structure of this multilevel VSM method has been designed in conformity with previous VSM approaches, e.g. [21][22]. Depending on the focus of the supply chain analysis, different value stream perspectives are provided (s. Figure 1).

The four different levels of detail are defined as:

- macro level: multiple companies or plants
- meso level: sub-network with transport links
- micro level: single company or plant
- nano level: single process

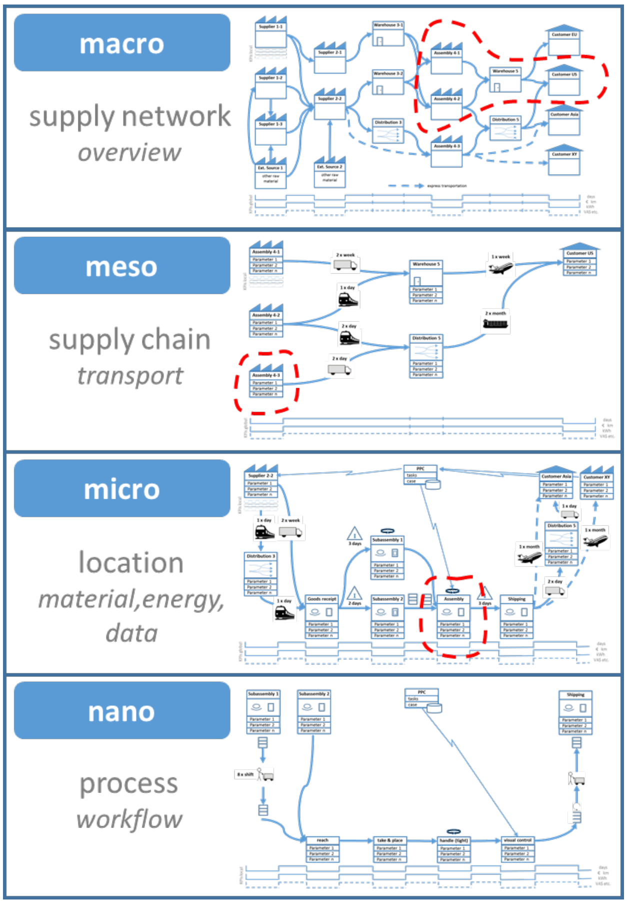

Figure 1 - Multilevel VSM method

On the macro level, a quick overview of the entire supply chain network can be achieved. The subsequent meso level provides further information with regard to transport modes linking the different supply chain partners. On the micro level, an intra-company view of a value stream is shown with product and information flows. This level corresponds to the usual VSM perspective of a specific location or plant. The underlying nano level is suited for a detailed process analysis and a subsequent workflow optimization.

Particularly in cross-enterprise applications, a broad usability of the developed approach is essential. To achieve a common and holistic VSM method, different parameters for various process types have to be defined (s. Figure 2). Beyond a default setting for all process types, flexible adjustments can be made depending on the specific supply chain.

The downstream-oriented product flow can be separated in material, energy and data-driven processes. The material or energy related processes can be further distinguished according to the production type (manual vs. automated) and production volume (single, series or mass production). The data-driven process types are either service, trade or management processes.

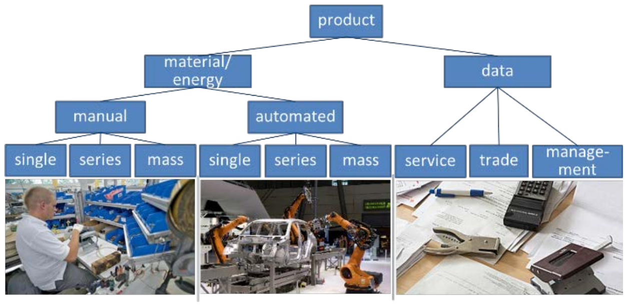

Figure 2 - Process types according to [24]

4.2 Data acquisition in supply chain networks

In consideration of the existing power structures in supply chains, which are primarily dominated by Original Equipment Manufacturers (OEMs), a new approach for a more efficient supply chain collaboration and communication is presented in the following. One major objective of this data acquisition approach is to determine the contribution of an individual actor with regard to the entire value stream. The data acquisition method is divided into six major steps (s. Figure 3).

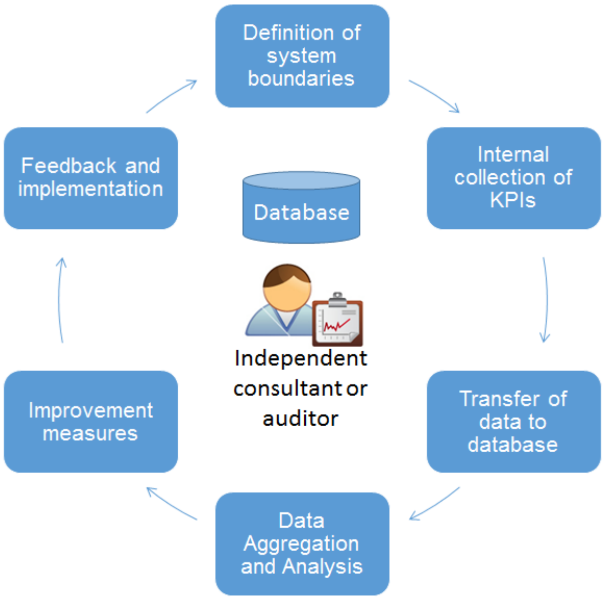

Figure 3 - Six step method to enhance supply chain collaboration and communication

First, distinct system boundaries for the subsequent data acquisition and analysis have to be defined. The decision of drawing extended or narrow system boundaries is very subjective. As a general rule, all those supply chain sections, which have a significant impact on the final product, should be considered. In practice, this might lead to very complex structures due to a huge number of suppliers. A way to cope with this complexity is to concentrate first on key suppliers and if required extend the analysis to further suppliers. During the second phase, company specific data, such as KPIs or other process data, are collected. This could be done separately by dedicated contact persons in each company or by an external specialist. As the company-specific pieces of information are often highly confidential, working with value stream data should be in the ideal case a task for an independent consultant or auditor. Having collected all relevant parameters, the data may be transferred to a central database. While reporting or integrating this process-related data in a central system, it is essential to maintain confidentiality related to other companies in the supply chain network. Then, the company-specific data can be aggregated to value stream data and analyzed on supply chain level. Different results of this value stream investigation can be expected in contrast to a pure intra-company analysis and optimization. Based on the value stream analysis phase, different measures for the improvement of the current value stream will be defined. In the last step, the supply chain actors inside the system boundaries get feedback on their contribution to the entire value stream. In addition, information with regard to the value stream analysis and optimization phase can be disseminated within the supply chain network.

All these necessary steps for data acquisition and analysis are in line with the management method Plan-Do-Check-Act (PDCA). Thus, for a steady improvement of the entire value stream, this procedure needs to be repeated continuously.

There are several benefits for the contributing supply chain partners. From an OEM perspective, the new data acquisition approach could be used as additional supplier evaluation tool that increases the efficiency of audits. Furthermore, this six-step method facilitates the data management of the entire supply chain network, from the supply of raw material to the delivery of the final product. Another benefit is the improved inter-company collaboration based on a central database and associated IT solutions.

The benefits for the supplying companies have to be seen in view to their customers. In OEM dominated supply chain networks, suppliers show a strong adherence to supply chain standards and requirements, as a stronger relationship to the OEM or the final customer ensures production and sales. In most supply chains, there are strong dependencies of supplying companies with regard to OEM's. Due to the dissemination of results, suppliers and other supply chain actors get sensitized to their contribution to the final product.

4.3 Mapping of cross-enterprise value streams

In addition to the described data acquisition and analysis procedure, the mapping of value streams in supply chain networks has to be standardized. With the help of a consistent catalogue of symbols and a common terminology, different supply chain partners get a common understanding of the value stream and are able to exchange knowledge and short-term modifications more efficiently.

Especially for specific VSM applications, there is no consistent use of symbols or calculation procedures. Parallel or repetitive processes (see Figure 4) serve as challenging examples.

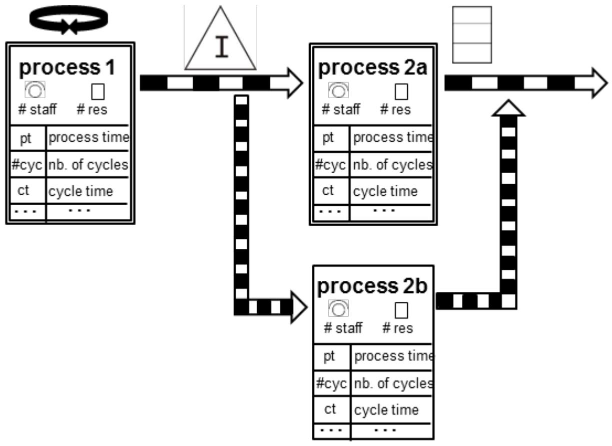

Figure 4 - Repetitive and parallel processes

Problems occur while aggregating cost or quality parameters, e.g. the determination of an overall scrap rate. The aforementioned approaches of multilevel value stream analysis and supply chain data acquisition are key concepts, which contribute to a standardized VSM method. In connection with this holistic VSM approach, integrated IT solutions will help to facilitate the collaboration in supply chain networks.

5 PROOF OF CONCEPT

5.1 Applicability and validation of the developed approach

The multilevel VSM approach has been tested successfully on nano and micro level for intra-company applications [25].

In addition, the developed VSM approach will be tested on meso and macro level in various industry sectors to ensure its general applicability. A validation in real industry and business environments will proof the suitability of the VSM method, especially with regard to cross-enterprise applications.

5.2 Risks and limitations

Regarding the presented VSM approach and associated data acquisition technique, some limitations have to be considered. The multi-sectoral VSM approach is limited to the analysis of companies, plants or processes in contrast to the described supply chain network models on country level. From a company perspective, a potential risk might be the lack of willingness to share crucial data with supply chain partners. Therefore, the gathering and analysis of data shall be a task of an independent and external consultant or auditor under a non-disclosure agreement.

6 CONCLUSION AND OUTLOOK

This paper provided a review of existing methods for the analysis and optimization of supply chain networks. To analyze collaboration and communication procedures in supply chains, a multilevel VSM approach and an associated method for data acquisition have been developed. These concepts are suitable for various process types.

Further steps are the validation of the VSM approach in real industrial or business environments followed by a proposal for standardization. This standardized VSM method shall be suited for a holistic analysis and optimization while facilitating collaboration and communication in complex supply chain networks.

7 ACKNOWLEDGEMENT

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9 BIOGRAPHY

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Efficiency-Oriented Risk Prioritisation Method for Supply Chains in Series Production

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Abstract
Efficiency in supply chain risk management (SCRM) is a major topic in industries with serial production and a complex supply chain due to limited management and financial resources. A high number of possible risk situations and intertwined processes create a more challenging environment for resource allocation. Managers cannot perform SCRM in all possible supply chain areas and hence have to decide where available resources should be utilised for highest possible risk reduction. This makes it important to quickly and systematically evaluate input and output relationships among risk mitigation actions to determine which actions are deployed first for efficient risk level reduction. This paper introduces a new SCRM method based on the failure mode and effects analysis (FMEA) in order to perform an efficiency-oriented risk action prioritisation. By considering the cost-benefit evaluation of identified risk mitigation actions for each assessed risk and by determining the implementation effort for risk mitigation actions, also considered as the cost for realising a specific risk action the method allows finding those risk and risk mitigation actions, which are most efficient for risk reduction and should be implemented first in the process of risk steering.

Keywords
Supply Chain Risk Management, FMEA, risk prioritisation, series production

1 INTRODUCTION

Businesses have become increasingly aware of the risk potentials arising from supply chains and studies show that supply chain risks and related business interruptions rank as the number one global business risk [1]. These figures clearly indicate an increasing need for a proactive risk management in the supply chain across industries.

It is apparent that companies must react to these challenges in order to fully recognise and manage risks in their supply chains, to understand the risks and the vulnerabilities in their supply chains in order to manage them accordingly. Studies [2], [3] showed that companies often have at best only partially implemented risk management systems in the supply chains or are simply not managing risks efficiently. Kersten et al. [4] stated that the biggest challenge in implementing supply chain risk management (SCRM) is resource limitation. This is of particular importance in environments of high complexity like supply chains in series production. A high number of possible risk situations and intertwined processes create a more challenging environment for resource allocation and opens up the problem where available resources should be utilised for highest possible risk reduction. [5]

In this paper, we present an efficiency-oriented risk prioritisation method for supply chains in series production to be used in industrial practice. This implies that the method should have a certain degree of practicability and ease of use.

2 EXISTING MODELS FOR SC RISK MANAGEMENT

2.1 Sources of supply chain risk

Multiple authors approached supply chain risk differently by categorising risks according to their occurrence in supply chains. For example supply risks and demand risks [6], supply chain risks related to design, quality, cost, availability, manufacturability, supplier, legal and environmental, health and safety [7] or the flow of material, information and money [8]. Other authors used the SCOR model structure to categorise risk along the dimensions plan, score, make, deliver and return [9] or introduced risk categories like disruption, delays, systems, forecast, intellectual property, procurement, receivables, inventory and capacity [10].

One approach was established by Christopher and Peck [11] and suggests separating risk in a supply chain context into three main categories: organisational risk sources, which are internal to the company, network-related risk sources, which are external to the firm but internal to the supply network, and environmental risk sources, which is external to the network. This classification clarifies the relevant dimensions of potential disruptions in a supply chain setting and therefore provides the basis for a comprehensive risk analysis. The three main categories can be further broken down into five distinct supply chain areas where risk can arise (see Figure 1). In order to evaluate the categories of demand, supply and process risk, four additional sub-categories are defined to indicate the impact area of respective risks. The sub-categories are quality, delay, loss and cost.

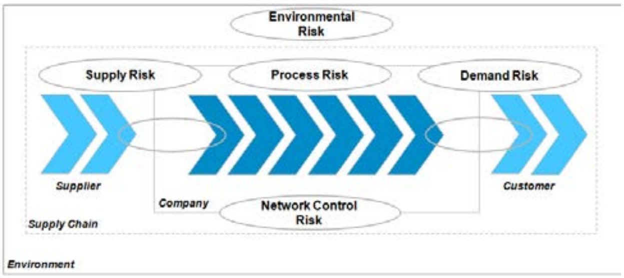

Figure 1 - Sources of supply chain risks [11]

2.2 Supply chain risk management

The SCRM process has developed from the traditional risk management function. According to the internationally established guideline ISO 31000 the basic risk management process consist of the steps: definition of risk management framework, risk identification, risk analysis, risk assessment and risk steering as well as two parallel steps of risk communication and monitoring. [12]

For SCRM, several researchers have adapted the generic process steps and aligned them with the purpose of managing supply chain risks. Similar as to the variation in traditional process steps, the SRCM process can have minor deviations (three steps approach [9], [13] or five step approach [14]) but it becomes obvious that the same core steps are part of the process in SCRM. The four steps approach as proposed by Norrman and Jansson [15] or others can be seen in Figure 2.

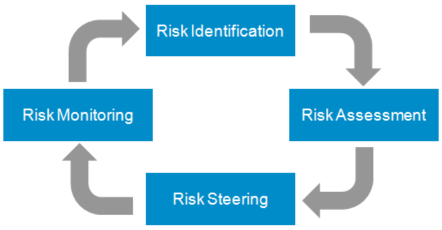

Figure 2 - Supply Chain Risk Management Process [17]

2.3 Methods of supply chain risk management

Most of the methods to perform and guide the risk management process originate from the classical risk management field and are mainly influenced by functions such as finance, quality management and systems engineering. [16] There are a very high number of classical risk management methods and tools available in literature, which are used for various kinds of approaches to risk management tasks [17]. However, due to specific characteristics of the SCRM compared to other functions it seems obvious that some are more suitable then others. Furthermore also Romeike [18] mentioned that the specific risk profile of a company has to be considered while selecting suitable risk management methods.

2.3.1 Methods for risk identification

For the process of identifying risks in a system, various methods are available. Romeike [18] proposed a categorisation into collection, creative and analytical methods.

2.3.2 Methods for risk assessment

The wide range of different risk assessment methods available need to be categorised. Multiple researchers distinguished between qualitative and quantitative methods for risk assessment [9], [19]. In the qualitative category the failure mode and effects analysis (FMEA) as well as the expert estimation are important methods [21]. The quantitative methods like fault tree analysis and scenario planning are often associated with higher effort as they are mainly based on hard facts and figures that need to be collected and structured to yield insight about the respective risks. The main obstacle is often the availability of suitable data. [18]

2.3.3 Methods for risk steering

The risk steering process is about determining concrete actions and strategies to mitigate and manage risk in supply chains. In order to identify the most suitable and effective strategies, quantitative and qualitative methods are available. [9]

2.3.4 Methods of risk monitoring

Risk monitoring is about the continuous controlling of the actual risk situation in the supply chain. Method in this risk management step are utilised in order to record identified risks for later review. This is often done by composing risk catalogues dedicated risk management IT-systems, which are company specific and additionally contain a specific risk categorisation. [16]

2.4 Prioritisation methods in supply chain risk management

2.4.1 General methods of risk prioritisation

In literature several risk prioritisation methods in SCRM can be identified in which risks are prioritised according to their importance for further assessment. It can be distinguished riskwise between known and unknown risks [9], [13], [15] and by risk prioritisation method (single, two or multiple criteria prioritisation) [5].

2.4.2 Prioritisation of product supply chains

The priorisation of a product specific supply chain is especially useful in business environments that handle a high number of different parts and components from different sources. This is often the case in manufacturing related sectors such as the automobile industry. Ziegenbein [9] proposed a risk portfolio with two dimensions (see Figure 3) To determine the degree for strategic importance of the product and its supply chain it is proposed to analyse its revenue potential. On the other hand, the degree of vulnerability of the product supply chain should be measured in past incidents that happened or the expected risk level.

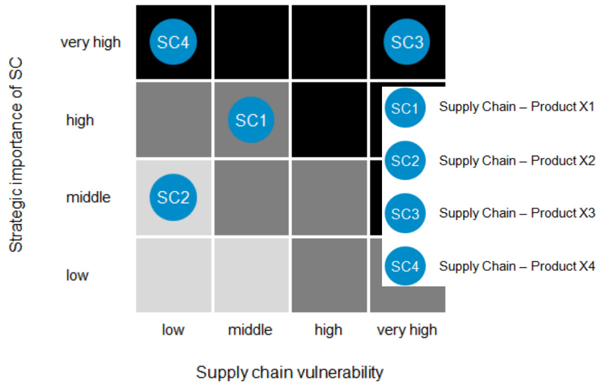

Figure 3 - Prioritisation of product SC [9]

Apart from a segmentation regarding products, supply chains can also be segmented according to the market, the sourcing characteristics or in view of its geographic or commercial environment. [22]

2.4.3 Prioritisation of resources

This was introduced by Lynch [23] where he prioritises the resources of the supply chain regarding their potential risk level. Resources can be labour force, technology, assets and relationships as well as processes.

2.4.4 Prioritisation of risk action effectiveness

Pujawan and Geraldin [23] developed a method to prioritise risk actions, which should be implemented at first in order to realise the most cost-effective risk reduction outcome in SCRM. For the procedure, the so called House of Quality method was utilised, which is also known as a part of Quality Function Deployment (QFD). The authors adapted the House of Quality for the purpose of SCRM. Engelhardt-Nowitzki and Zsifkovits [24] used a portfolio visualisation technique with the two dimensions "risk action benefit" and "risk action implementation effort" to prioritise possible risk actions.

2.5 Critical reflexion of the state of the art

Based on the state of the art in SCRM it was possible to develop a general SCRM framework (Figure 4) which can be used by industry. However, it is of particular importance for practice to have a simple method based approach for the process of reducing risk in the supply chain in order to ensure a systematic and guided procedure for risk management [5], [26]. Here a lack of methodical support in risk steering can be identified. [23] needs intensive knowledge about the House of Quality calculation procedure. Additionally the authors stated that this method requires intensive qualitative data collection from within the focal company.

The FMEA is an often used and applied method, which can be easily adapted for the purpose of managing risks in a supply chain. Several possibilities have been outlined in literature, to improve identified weaknesses of FMEA through methodical amendments. The high value of utilising the FMEA also in practical SCRM is specifically stated by [26] in mentioning the benefits to give managers a systematic step-by-step method for risk evaluation in supply chains. An approppriate risk steering method based on the FMEA shall be introduced in the following chapter.

3 PRIORITISATION METHOD FOR EFFICIENT RISK REDUCTION IN SUPPLY CHAINS

3.1 General procedure and overview of the method

Risk identification: Four sub-steps are necessary in order to ensure detailed and comprehensive risk identification. First, the supply chains, which are

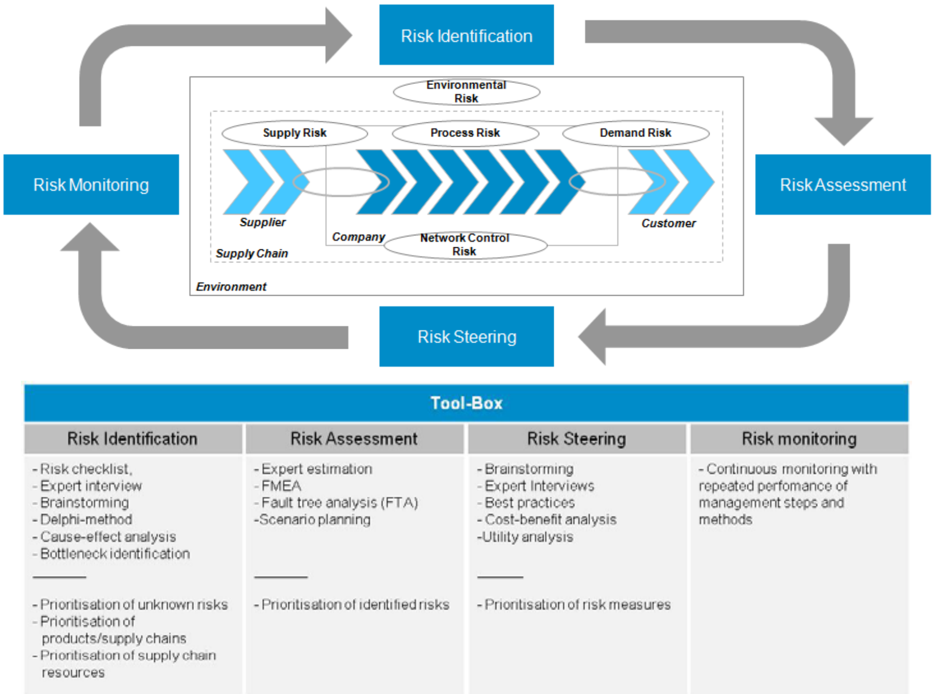

Figure 4 - Supply Chain Risk Management Framework

important for the risk assessment, must be selected. This is done by utilising a portfolio prioritisation analysis ([9] see Figure 3). Then the selected supply chains are mapped in order to visualise the structure and possible weak points. Next, the actual risk identification takes place in a workshop with Supply Chain (SC) Risk Experts. Finally, all identified risks are summarised and categorised according to their sources and impact areas in a risk catalogue.

Risk assessment: The assessment step consists of two sub-steps and will be based on the FMEA, which is introduced as the pivotal SCRM method. The selected risks should be analysed and evaluated in a workshop of SC Risk Experts according to the respective causes and impact potentials. Then, an individual rating should be assigned to each identified risk. The rating considers the risks in terms of the likelihood of occurrence, the impact severity and the probability of detecting the risk. After the rating of risks and calculation of respective risk levels, a prioritisation takes place in order to define the top risks of the SC.

Risk steering: Four sub-steps lead to the final outcome of the procedure. First, risk mitigation actions for top ranked risks must be developed and assessed. Mitigation actions should be developed by SC Risk Experts based on their experience. Following this a re-assessment of the top risks under consideration of anticipated changes to risk levels due to risk mitigation actions is performed. After the initial two steps the FMEA extension takes place by evaluating the implementation efforts for risk mitigation actions. The Improvement Index (IMIN) for top risks is then calculated based on the old and anticipated new risk priority number (RPN). Finally, the IMIN for top risks as well as the effort value for action implementation are transferred in a portfolio. The portfolio is made up according to [24] by the dimensions of "implementation effort" and "risk reduction potential" in order to determine the most effective risk mitigation actions for implementation. Based on portfolio, it can be decided, which supply chain risks with respective risk mitigation actions should be approached first in order to reduce the risk level of the supply chain most efficiently with available resources.

Risk monitoring: In this step, the risk catalogue as well as the implementation procedure for determined risk actions should be managed. This means, a constant monitoring of those risks in the catalogue is necessary in order to ensure continuous re-evaluation of risk levels by the SC Risk Team. Additionally the progress of implementation work to mitigate the top risks in the supply chain should be observed and if necessary adapted to changing environments.

3.2 Supply Chain Risk Management-FMEA

After assessing all SC-risks by SC Risk Experts, risk mitigation actions and the best selection of a risk management program are necessary. The risk management program consists of the selected risk mitigation actions, which are determined to be implemented to reduce the risk level in the SC.

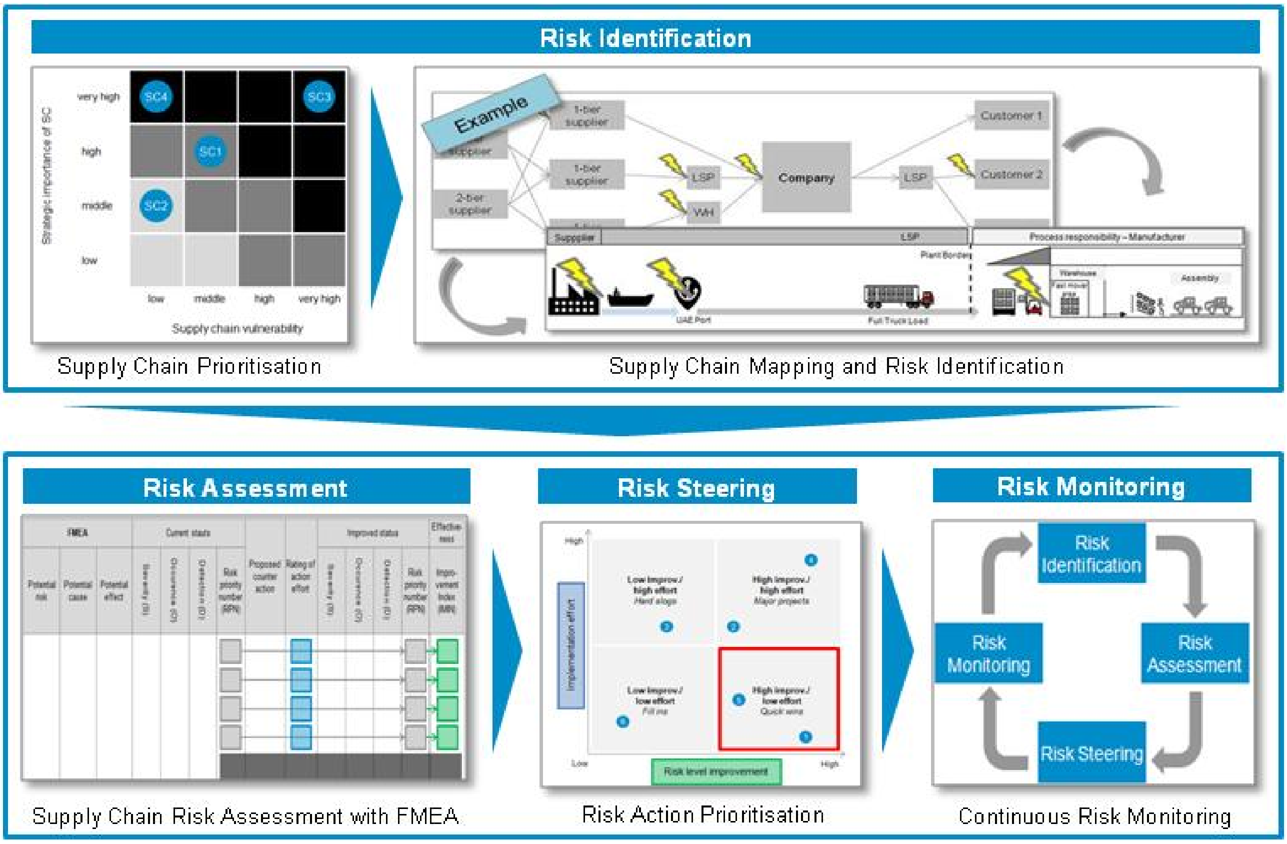

Figure 5 - General overview of the SCRM method for efficiency-oriented risk prioritisation

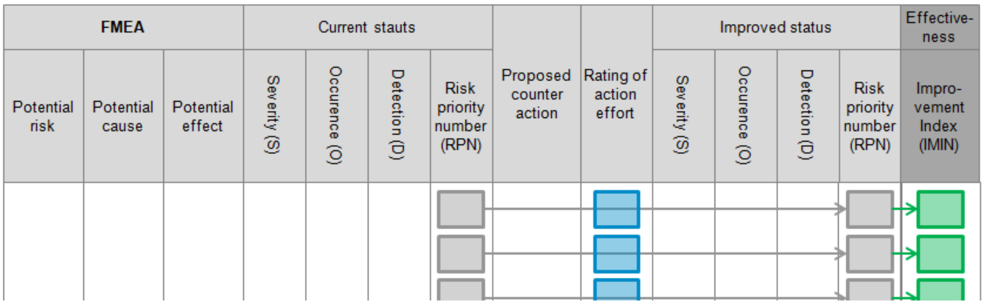

Figure 6 - SCRM-FMEA including IMIN and effort rating

The rating of counter actions in terms of the expected overall effort for implementing them (Index 10='low' to 50='very high') and the assessment of the risk priority number to be expected in the improved status enables the calculation of an improvement index IMIN = 1 - (new RPN / old RPN) as extension of the FMEA (Figure 6) enables the effective prioritization of measures (Figure 7).

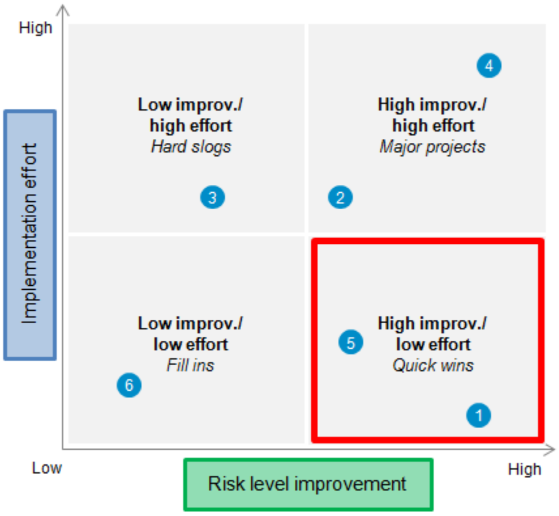

Figure 7 - Cost-benefit prioritisation portfolio

4 CONCLUSIONS

The presented method was tested with an inbound supply chain of a vehicle producer with a final assembly in the Middle East and a global network of suppliers. Most of the parts and components for the vehicles are sourced from Europe and the US. The production can be characterized as small-scale series with little variants. In order to show the effectiveness of the risk prioritisation method the risk level of the original inbound supply chain of the vehicle cabin was determined. The risk assessment step (see 3.1) of the supply risks was executed by SC experts. The total supply chain risk level was RPN 1971. In the risk steering step counter-measures for the highest risks that account for 75 % of the total supply chain RPN were taken. With a total implementation effort of 160 (scale from 10 to 50) the total risk level of the added RPN-values dropped from RPN 1.971 to RPN 1.053.

Taken limited resources of 50% of the overall effort for risk reduction (80 of 160 index points) the risk reduction results based on a traditional FMEA (improving those risks with highest RPN) had 12% less benefit on the total risk of the supply chain than the SCRM-FMEA (improving those risks with highest Improvement Index IMIN). With the same effort the total supply chain risk could have been reduced from RPN 1.971 to 1.257 with the prioritisation of the SCRM-FMEA instead of RPN 1.422 with the traditional FMEA. The method therefore could prove its effectiveness by selecting those risk countermeasures which are most effective with given effort limitations. The focus of action though moved from the individual risk level to the supply chain risk level.

The limitation of this method however is the lacking consideration for risk actions influencing each other what is an inherent weakness of the FMEA in general. But the advantage of having an established and well known method with limited complexity and required input may be of value for the practical use in industry. The usefulness for other industries with less complex supply chains than in series production or other production types still needs further research.

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Lean Engineering – Current Implementation and Opportunities in the Manufacturing Industry

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Abstract
To ensure competitiveness manufacturing companies have to increase both effectiveness and efficiency within their product development. In order to focus on value creation and to eliminate waste the concept of Lean is applied to engineering. This paper is based on a survey of 100 companies in the manufacturing industry. It aims at the analysis of the current implementation of Lean in engineering and the identification of key success factors. Regarding the current implementation of Lean in engineering 19% of the assessed companies can be characterised as Lean Performers. These companies have a significantly increased R&D performance compared to Lean Followers. Success factors that differentiate performers from followers are for instance modularised product designs and agile, fast-cycle processes. These two principles are analysed more detailed through quantitative data in order to understand their successful application and specific benefits. Based on the survey results managerial implications for the successful implementation of Lean in engineering are presented.

Keywords
Lean Engineering, product development, modularised product design, agile processes

1 INTRODUCTION

In the manufacturing industry companies have to adapt to a highly competitive environment and to an increasing complexity, driven by variety in products and production processes. To master these challenges increasing both effectiveness and efficiency in product development is a crucial aim. Companies cannot afford waste within their product development and therefore focus on the adaption of lean principles to the development of new products. Lean Management is capable of significantly increasing efficiency in manufacturing companies and is widely applied in production, but not yet in Engineering. This paper presents the current status of implementation of Lean in engineering as well as key success factors for the adaption of Lean to product development.

2 LITERATURE ON LEAN IN ENGINEERING

2.1 Lean Management

The main focus of Lean Management is the concentration on value creation and the elimination of waste [1]. Originally derived from the Toyota Production Systems (TPS) it has been applied to production since the 1990s with great success. The overall goal of lean management is the creation of a truly lean company [2]. A major contribution to the further diffusion of lean management is provided by the adaption of Lean to Engineering, often referred as Lean Product Development (LPD), Lean Development (LD) or Lean Innovation (LI) [6].

2.2 Approaches for Lean in Engineering

Based on the understanding of Lean Thinking different authors have proposed approaches for the application of Lean to product development. The term Lean Product Development was in particular characterised by MORGEN and LIKER [3] who similarly to WOMACK ET AL. [1] analysed the practice at Toyota and drew their conclusions for product development. Based on their observations they introduced the Lean Product Development System (LPDS) as a descriptive model for the product development practise at Toyota. The LPDS is a socio-technical system consisting of three subsystems – process, skilled people and tools & technology – and 13 subordinated principles. These principles for instance recommend the development of a Chief Engineer System or the creation of a levelled product development process flow.

A more holistic approach focusing on the entire innovation process is presented by SCHUH [4]. The Lean Innovation approach aims at the adaption of lean principles to R&D management focussing on both increases in efficiency and effectiveness. Lean Innovation is comprised of four phases with 12 subordinated principles. The phases are named prioritize clearly, structure early, synchronise easily and adapt securely. While principles within the first phase prioritize clearly are addressing strategic issues of product planning, the principles within the phase structure early are targeting the design of products, product architectures and product programs. Synchronise easily has a strong focus on increasing efficiency by optimising the product development value stream. The last phase adapt securely addresses the need of a lifecycle approach by suggesting principles like innovation controlling or release management.

WARD and SOBEK [5] are focussing on Lean Product and Process Development. In this context a System for Lean Product Development is introduced which consists of five core principles: value focus, entrepreneur systems designer, set-based concurrent engineering, cadence, flow and pull, and teams of responsible experts.

A comprehensive literature overview of suggested lean principles in product development is provided by HOPPMANN ET AL. [6]. who conducted an extensive content analysis in order to investigate existing approaches and create a coherent framework consisting of eleven Lean Product Development principles.

3 FRAMEWORK FOR THE ASSESSMENT OF LEAN IN ENGINEERING

In order to assess all aspects of Lean in Engineering a framework was set up based on the analysis of existing lean principles in product development. The framework includes the dimensions product, process, leadership and behavior, and enablement and tools. In the product dimension, for instance, Lean can be realized by a modularized product design based on a strategic positioning and clear product requirements. Lean processes can be achieved by ensuring an agile project management and establishing fast feedback loops.

The considered factors contributing to the implementation of Lean in engineering are structured in the four mentioned dimensions and listed in the following:

Product:

- Strategic positioning
- Holistic and detailed roadmapping
- Transparent product requirements
- Modularised product design
- Optimized product range

Process

- Solution-oriented design sets
- Agile, fast-cycle processes
- Flexible workload levelling
- Sequencing and reduced bottlenecks

Leadership and behaviour

- Proactively handle uncertainty
- Fact-based, fast-cycle steering
- Cross-functional collaboration
- Empowered project manager

Enablement and tools

- Experience- and expertise-driven development
- Speed-supporting tools
- Single source of truth

All factors were analysed regarding their importance and degree of implementation at the participating companies.

4 SURVEY ON THE IMPLEMENTATION OF LEAN IN ENGINEERING

4.1 Survey design and data

The survey was conducted as a print and web survey and was supplemented by individual interviews of participants. In total 100 valid responses were collected. Detailled information on the respondents is presented in table 1.

	Category	Num.	%
Industries	Automotive – OEM	7	7%
	Automotive - supplier	17	17%
	Machinery manufacturer	32	32%
	Component manufacturer	32	32%
	Others (e.g. household)	12	12%
Annual turnover	< €0.5 bn	34	34%
	€0.5-1 bn.	16	16%
	€1-10 bn.	47	47%
	> €10 bn.	3	3%

Table 1 - Overview of survey respondents

Within the survey both qualitative and quantitative data was collected. Each of the 16 factors of the introduced framework was assessed with three types of questions:

- Importance of the factor [Likert scale]
- Qualitative assessment of the degree of implementation [1,4]
- Quantitative assessment of key performance indicators [KPIs]

The assessment scheme will be illustrated using an example. The qualitative assessment regarding the use of modularised product designs was performed using the following four answer possibilities:

(1) No modularisation across product lines.

(2) Modularisation across few product lines. New products developed with limited re-utilisation of existing modules.

(3) Modularisation across majority of product lines. New products are developed with high re-utilisation of existing modules, but without clear top-down targets regarding re-use ratios.

(4) Modularisation across all product lines. High re-utilisation of carry-over parts enforced through structured process with clear top-down targets.

Each answer possibility represents a different degree of implementation within a manufacturing company. For further analysis key performance indicators were assessed. For modularized product design exemplary indicators are the percentage of products build from a modular product system or percentage of carry-over parts typically used. The assessed KPIs were also used to check the validity of the qualitative assessment results. In total 22 quantitative KPIs were collected.

4.2 Survey results

In this chapter significant findings from the survey results will be presented. The statistical analysis of the survey data is based on correlations between both qualitative as well as qualitative and quantitative questions. The results were analysed using a two independet samples t-test. Results with p-values lower than 5% were considered significant. The applied test is based on the likely assumption of an equal distribution within each sample and is a recognised method for survey data analyses.

4.2.1 Use of methods of Lean Engineering

In the first step the use of methods of Lean Engineering within the survey sample was analysed. The general application of Lean was assessed using the following answer possibilities:

Lean methods in engineering

(1) …are not yet considered.

(2) …have not yet been implemented.

(3) …have been implemented in a few projects.

(4) …are routinely executed in most projects.

(5) …have become the new standard.

Companies who responded with answer (4) or (5) are considered Lean Performers. 19% of the participating companies are characterized as Lean Performers while the remaining 81% are considered Lean Followers. The distribution is shown in table 2.

Q 1.0	*Use of Lean methods in engineering*				
Answer	(1)	(2)	(3)	**(4)**	**(5)**
number	21	28	32	**15**	**4**
percent	21%	28%	32%	**15%**	**4%**
"19% of the respondent companies can be described as Lean Performers"					

Table 2 - Use of Lean methods in engineering

Based on this initial charaterisation further correlations were analysed. A basic assumption is that the application of Lean results in a better performance. Therefore, the assessment of relevant performance indicators was compared between Lean Performers and Lean Followers. Since Lean focusses on the elimination of waste an improvement regarding time and expenditure within product development projects would be a supposed result. Therefore, the according hypotheses were tested. First it was tested whether Lean Performers have a higher share of projects completed in time. The results presented in table 3 strongly support this hypothesis showing a significant correlation between the application of Lean and the completion of projects in time.

Q 1.1	**Lean Performers**	**Lean Followers**	**total**
number	19	81	100
mean	71.2%	48.7%	53.0%
p-value	0.24%		
"Companies that use methods of Lean Engineering routinely have significantly more projects completed in time."			

Table 3 - Effect of Lean application on projects completed in time

Secondly the analogues hypothesis regarding projects completed in budget was tested. This hypothesis could also be verified which is illustrated by the results shown in table 4.

Q 1.2	**Lean Performers**	**Lean Followers**	**total**
number	19	81	100
mean	74.0%	55.5%	59.0%
p-value	3.69%		
"Companies that use methods of Lean Engineering routinely have significantly more projects completed within budget."			

Table 4 - Effect of Lean application on projects completed within budget

No significant correlation between the application of Lean and the reduction of development time could be identified due to the high variance of new product development durations within the sample. A detailed analysis of this effect would require a bigger sample and a differentiation of subsamples regarding the type and the complexity of the developed products.

Inorder to find out what sets Lean Performers appart from Lean Followers the 16 factors were analysed regarding significant difference between the two groups. Two factores with significant correlations were identified as particular interesting by the authors and are analysed more detailed in the following two chapters. These factores are modularised product design and agile, fast-cycle processes.

4.2.2 Use of modularised product design

The use of modularised products is considered as one important factor of Lean in Engineering within the product dimension. The analysed data supports the hypothesis that modularisation is a differentiating factor of Lean Performers. This is shown by a significantly higher degree of implementation (see table 5). The characterisation of the degree of implementation was described in chapter 4.1.

Q 2.1	Lean Performers	Lean Followers	total
number	18	80	98
mean	3.0	2.4	2.5
p-value	0.16%		
“The implementation of modularisation is one differentiating factor of Lean Performers”			

Table 5 - Use of modularised product design

To further investigate the use of modularisation the sample was grouped in practitioners and non-practitioners of modularised product design (MPD). Practitioners are those companies who assessed the degree of implementation with answer (3) or (4). Since a high share of Lean Performers are as well MPD practitioners comparable results on project performance can be identified. These results are not further discussed in this paper. However, further correlations with other qualitative factors could be identified. One hypothesis is that modular product design is enabled by experience- and expertise-driven development. In order to design and reuse robust modules companies need to establish a system for structured knowledge management. The hypothesis is that practitioners of modularised product design make more use of knowledge management systems. Looking at the data shown in table 6 it can be identified that MPD practitioners have a higher utilisation of knowledge management by 13.6%.

Q 2.2	MPD practitioners	MPD non-practitioners	total
number	51	48	99
mean	2.5	2.2	2.4
p-value	1.47%		
“MPD Practitioners tend to use Knowledge Management Systems more frequently than their competitors.“			

Table 6 - Use of Knowledge Management

4.2.3 Use of agile, fast-cycle processes

Within the process dimension one proposed factor is the establishment of agile, fast-cycle processes. The underlying hypothesis is that Lean Performers tend to have processes divided in more and smaler phases in order to allow iterative feedback loops and fast recalibration. The analysed data shown in table 7 indicates that Lean Performers make more use of agile, fast-cycle processes.

Q 3.1	Lean Performers	Lean Followers	total
number	18	79	97
mean	2.9	2.6	2.7
p-value	3.02%		
“Development processes at Lean Performers tend to span more, smaller phases, than at Lean Followers”			

Table 7 - Use of agile processes

A major benefit of short phases and fast feedback loops is the possibility to perform a fast recalibration. This can be important in particular when target costing is applied in new product development. Deviations from target costs can be identified early in the process and counteractive measures can be taken. The resulting hypothesis is that practitioners of agile have a lower deviation from product target costs in comparison to non-practitioners. This hypothesis was tested and verified with practitioners having a significantly lower deviation from target costs (37.0% less). The supporting data is presented in table 8.

Q 3.2	AP practitioners	AP non-practitioners	total
number	45	29	74
mean	9.1%	14.6%	11.3%
p-value	0.54%		
“Agile practitioners have a significantly lower deviation from product target costs than non-practitioners“			

Table 8 - Effect of agile on target cost deviations

A high percentage of companies was characterized as agile practitioners (60.8%), while a lower share was assigned to the Lean Performers (19.0%). Therefore it is necessary to additionally evaluate the effect of the application of agile methods on the R&D performance. Analysis of the present data shows that companies practicing agile methods have a significantly higher share of projects completed in time (26.9% higher; p=0.8%) and projects completed in budget (29.0% higher; p=0.3%).

5 OPPORTUNITIES IN MANUFACTURING INDUSTRY

The global benchmarking of 100 companies shows gaps between different industries. While 30% of OEMs in the automotive and 35% of companies in machinery industry are taking advantage of lean methods in engineering, only 5% of automotive suppliers and 15% of component manufactures are doing likewise. Considering the survey results there are significant opportunities for increasing product development performance using methods of Lean Engineering. In the following, two key concepts will be discussed and managerial implications from survey results will be presented.

5.1 Modularised product design

Lean Performers are setting themselves apart from Lean Followers by applying a modularised product design. They have identified the benefits of modular product platforms as a basis for a diversified product portfolio. Modularisation can be the key enabler for the reduction of internal complexity, while responding with product variety to a complex external environment. Modularised product design is predominantly realised by automotive OEMs (71%) and machinery manufacturers (66%), while automotive suppliers (47%) and component manufacturer (38%) are lagging behind. In order to close this gap it is important to understand how to start the development of a modular product platform. In current literature various approaches can be identified that deal with the planning, design and implementation of modular product platforms. An overview of recent advances is presented by SIMPSON ET AL. [7]. To effectively implement the development of a modular product architecture or platform it is recommended to execute the development in a specific interdisciplinary process which is superior to the development of a single product line (*see figure 1*).

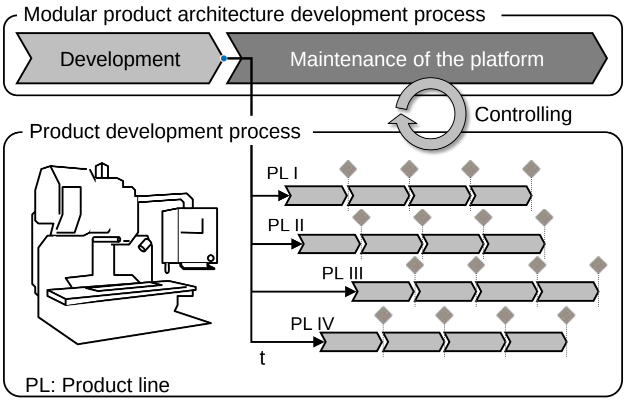

Figure 1 - Superior development process for modular product architectures [8].

This is comprehensible considering the fact that main benefits are achieved by applying standardised modules to different product lines within the product portfolio. To successfully start a modularised product design it is proposed to define a company specific process for modular product architecture design and subsequently implement and validate the process with a suitable pilot project. For the process the following stages suggested by SCHUH ET AL. [8] can be used:

1. ***Identification of potentials***, which leads to the requirements specifications
2. ***Definition of standards***, which leads to constituent features
3. ***Definition of platform structure***, which leads to the modular product architecture

For each phase a configuration of different methods can be used.

5.2 Agile, fact-cycled processes

According to the survey results in the process dimension a significant increase in R&D performance can be achieved by applying agile methods to the product development process. Instead of having long phases, e.g. like a traditional waterfall model [9], the process should be divided into smaller phases with regular feedback loops and frequent testing activities. Originally developed in software egineering the Scrum methodology is the most used agile methodology [10]. Key features of agile are adaptability to change and an iterative process strongly focussing on customer value and customer acceptance [11]. Lean Performers are successfully applying these principles to the development of physical products. In order to start the journey towards a more agile product development process it is recommended to start on a smaller project level. In this context SCHUH ET AL. [12] introduce the concept of takt time to the product development process. This concept is suitable to be integrated in a conventional stage-gate process and is based on the idea of dividing long development phases into smaller takt cycles, which range between 5 and 20 working days. The tasks for one takt (comparable to a sprint in Scrum methodology) are planed at the beginning of a takt and then visualised on a task board. During the takt daily team meetings are held to discuss progress and the end of a takt is marked by a review meeting. The concept of takt time is illustrated in figure 2.

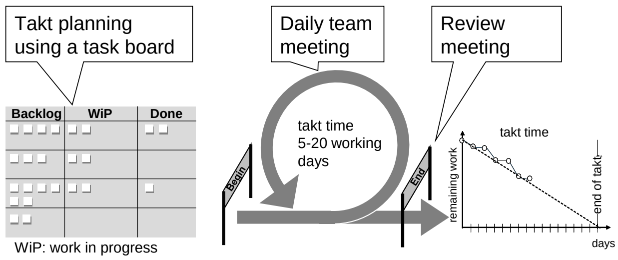

Figure 2 - Application of takt time in product development [12].

Schuh et al. [13] further present an industry example where the concept of takt time is successfully applied to the product development of a gas turbine. Through the application of takt time it is possible to enhance synchronisation and to foster an adaptive and iterative working environment.

6 CONCLUSION

The presented survey argues that companies in the forefront of applying Lean to engineering are achieving an increased R&D performance. They have a significantly higher share of projects completed in time and budget. These Lean Performers are especially advanced in two key success factors: modularised product design and agile, fast-cycle processes. Modularised products enable an effective management of internal complexity and have a direct benefit regarding time and budget through the structured reuse of standardised modules. The application of agile to the product development process is able to effectively increase the adherence to schedule and budget. Furthermore, a significant correlation between the use of agile and lower deviations from product target costs can be identified. In order to improve R&D performance it is proposed to focus on the two analysed factors. For the design of modularised products it is important to conduct the architecture design within a process which is superior to the existing product development process. To fully utilise the potentials of this principle standardised modules need to be structured for the use in different product lines within the product portfolio. Regarding the first steps towards a more agile process it is proposed to start with the introduction of takt time and the use of a task board to a product development team. This approach has proven to be an effective way to start the journey. Taking into consideration the survey results and the managerial implications companies have the opportunity to effectively establish Lean in engineering.

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8 BIOGRAPHY

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STREAM D

Enterprise Design and Integration

Session D1: Product Life Cycle Engineering

Session D2: Learning Factories

Session D3: Industry 4.0 - The Internet of Things

Session D4: Enterprise Engineering Tools

Session D5: Human Interface

Measuring the Economic Impact of Life Cycle Management and Service Performance

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Abstract

The management of product generations requires a holistic life cycle management approach, especially when it comes to the question of obsolescence management of products and components. This paper presents an innovative tool called "Life Cycle Index" which enables manufacturers as well as industrial end-users to assess and evaluate the productivity potentials and risks of their installed base. The tool has been developed by an industrial manufacturer of process control systems in Germany and was used –to date- to index more than 200 customer plants concerning the life cycle status of / in the installed base. The paper present the major results of the index interviews and shows how the innovation of the life cycle index made it possible for the first time to measure the benefit of life cycle management. Based on these experiences, the industrial users were able to benchmark and leverage their life cycle benefits. It also enabled the manufacturer to design a new service level management portfolio to better meet customer demands and to raise service profits. The paper also shows how this technology was used to develop the index further on and how to apply the technology on entire service processes to evaluate and optimize the service performance.

Keywords

Life Cycle Management, Service Management, Life Cycle Productivity

1 INTRODUCTION

Increasing competitive pressures in many industries, coupled with declining perceptions of customer service, have led to increased attention to service recovery in recent years. Service failures can lead to negative disconfirmation and ultimately dissatisfaction, though appropriate service recovery efforts may restore a dissatisfied customer to a state of satisfaction. Thus, companies with the ability to react to service failures effectively and to implement some form of service recovery will be in a much better position to retain profitable customers.

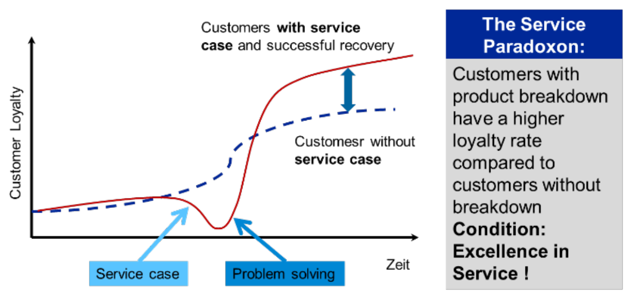

Figure 1 - The service paradox: Excellence in Service fosters customer loyalty [1]

More than 30 years ago, Etzel and Silverman called this phenomenon "the service recovery paradox" [1]. Their studies show that the customer loyality to a product can even be fostered and raised by delivering excellence in service after a breakdown. Customers might even think more highly of a company after it has corrected a failure with a prompt service response, compared to how he or she would regard the company if no service failure had happened (see figure 1). In today´s daily business life we find such statements in similar expressions like: "The first machine is sold by the sales people, the second one by the service department. Both findings show that a successful service (recovery) is the key to long lasting customer partnerships.

On the other hand, recent studies among German companies in the sector of machinery and plant construction show that 75% of the possible service business is executed by competitors or third party suppliers. Manufacturer only achive only 25% of the possible revenues in this market. The following paper shows how a multinational company in the area of process automation has improved its service business towards a proactive service partner for their customers over the entire life span of their products.

2 A LIFE CYCLE INDEX FOR PROCESS CONTROL

Process control systems nowadays can easily have a lifespan of more than 20 years – provided that they are looked after and maintained correctly. Thanks to the "Life Cycle Index", operators can now for the first time record, assess and plan the productivity potential and risks of their control system installations in an objective manner. [2]

When it comes to process control systems, plant operators are increasingly assessing new installations or upgrades on the basis of the “contribution they make towards achieving long-term productivity targets”. [3] Life cycle management means here “… not talking about forecasting the future, but shaping it…”.[4] There are two basic strategies here: In some cases, the focus on an increase in productivity lies on maximum output whilst investing the same amount of materials and energy. However, more often, plant operators try to achieve the planned sales volume with minimal outlay. The more efficient use of resources is therefore an important motivating force for companies looking to achieve lasting competitive advantages.

As far as the “minimal use of resources” is concerned, operators want to know which follow-up costs will be incurred after installation and how the control systems can help to ensure that processes are managed efficiently. Increasingly, they look at the entire life cycle of the production facility, which can often mean a period of more than 30 years. This poses major challenges for control system manufacturers, as the lifespan of the individual components which make up a control system can vary considerably (see figure 2).

Figure 2 - Management of product generations - Factor 10 in service life

Only the cabling roughly matches the lifespan of the entire production facility, although I/O modules and controllers can have a lifespan of 20 and 15 years respectively. Technical obsolescence and innovation cycles mean that computers and software remain economically viable for only five and three years respectively. Successful life cycle management for process control systems must address this problem from the point of view of the compatibility of hardware and software components. [5] Only in this way can companies protect their investments in automation technology in the long term and operate a user’s individual applications in a future-proof manner.

3 LIFE CYCLE MANAGEMENT FOR PROCESS CONTROL EQUIPMENT

3.1 The four life phases of control systems

With this in mind, the manufacturer has put in place active life cycle management for his process control systems. This is based upon a group-wide, standardized life cycle model which applies to all parts of a process control system. It covers the hardware and software used at the control level, the controllers, the network and the I/Os (see figure 3).

Life cycle system calendar

Jear	-1	Today year	+1	+2	+3	+4	+5	…
System software V3				A	A	A	A	A
System software V2	A	A	A	A	A			
System software V1	A	C	C	C	L	L	L	L
Controller C				A	A	A	A	A
Controller B	A	A	A	A	C	C	C	C
Controller A	L	L	O	O	O	O	O	O
I/O B	A	A	A	C	C	C	C	C
I/O A	L	L	O	O	O	O	O	O

?

Figure 3 - Life cycle strategy and compatibility

All of the manufacturer´s control systems are designed to allow continuous further development (evolution), but the useful life of the individual components differs, although they run through identical life cycles. Especially when a component is nearing the end of its life cycle this principle allows migration to what is then the current product generation. By synchronizing the various lifespans, the manufacturer is able to ensure that the entire process control system is technically up to date over its whole life cycle. The concept subdivides the life cycle of a product into four distinct phases – active, classic, limited and obsolete. Every product goes through these phases, which differ in terms of the product support and available services.

The modular structure of the I&C equipment and the staggered time plan offer two benefits: the life of the plant can be supported on a long-term basis and technological progress can be integrated into process control on an ongoing basis. Moreover the unequivocal allocation of the components to product life phases provides reliable information about the availability of spare parts and the product support the supplier can offer. This planning certainty not only increases overall system reliability but also improves the performance and availability of the plant. [6]

3.2 Objectivity thanks to the Life Cycle Index

The use of life cycle management for process control systems provides an important opportunity to optimize the benefits of such systems over their entire lifespan. In order to maintain or even increase the productivity of a plant on a sustained basis, it must be possible to assess its performance over its entire life cycle. The manufacturer has therefore developed a Life Cycle Index which allows it to measure and assess the productivity status of process control systems on an ongoing basis. The three stage approach is shown in figure 4.

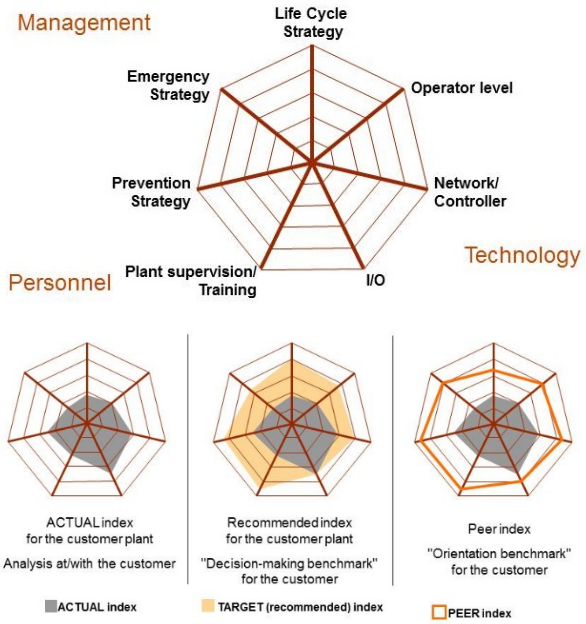

Figure 4 - The Life Cycle Index

The Life Cycle Index provides objective key data for analysing, assessing, documenting and controlling the productivity status of a plant. The key data reveal not only potential strengths but also productivity risks within the context of the performance targets set by the company management. The resulting index profile provides a basis for planning short-, medium- and long-term packages of measures for maintaining or increasing the productivity of a plant. [7]

3.3 Everything is put to the test

The Life Cycle Index designed to offer an integrated assessment approach takes into account automation technology and primarily the quality of the system management with respect to the processes and strategies in place for life-cycle-oriented future planning, failure prevention and emergency measures. The index also assesses the qualifications of the members of staff at the plant. From a technical point of view, ABB experts assess for example the age and condition of the network, the controllers and the I/O level and not just the equipment in use at the control level. The sub-index "personnel" takes into account aspects such as individual staff qualifications, their further training and the ongoing training of new recruits. After all, the special knowledge of technical staff at a plant frequently offers great potential for achieving further increases in productivity. Conversely, inadequate staffing levels may necessitate long-term training measures in order to combat risks to productivity resulting from a lack of well-trained? personnel.

However, experience shows that efficient system management is the most important factor when it comes to maintaining and increasing plant productivity. For this purpose, the index examines the effectiveness of the processes defined by the plant operator and records e.g. the quality and response time the plant operator needs to provide the know-how for fault location, to identify the required spare parts and organize their delivery if problems arise in the plant. The index depicts not only these technical and logistical processes but also the quality of the processes relevant to company management and strategy. The assessment includes aspects such as the company management's planning and budgetary horizon or the effectiveness of the continuous improvement processes in place. There is often considerable hidden potential for increasing productivity in this area, too. This can be directly exploited using coordinated measures such as consultancy services and software tools.

3.4 The control system benchmark

Being part of the "plant indexing" process, plant operators are provided with a detailed analysis of the strengths and weaknesses of their process control system and the current productivity status of their plant. Thanks to ABB's many years' experience, it is possible to provide anonymized index profiles for use as a benchmark when determining the current position in relation to the sector average or to relevant, comparable plants.

For the customer it is crucial, however, to create his own "target index profile" which results from the long-term objectives for plant operation. Any differences between the target profile and the actual profile provide the starting points for the planning, implementation and budgeting of appropriate measures. This also gives operators the opportunity to visualize the effects of their coordinated measures or long-term life cycle agreements and to monitor the reaching of their objectives continuously by means of future indexing. In order to monitor the progress, a continuous re-indexing of customer plants ("controlling") can be established (see figure 5). There is also the option of concluding life cycle agreements, which may have a duration of three to approx. ten years depending on the customer's requirements. They contain predefined packages of measures comprising software and hardware upgrades and other specific services with fixed prices and implementation schedules.

Time, activity and cost plans like these ensure clarity as far as the follow-up costs of an investment are concerned. Planning the entire life cycle of all components also ensures that they remain future-proof and protects the customer's investment in its control system.

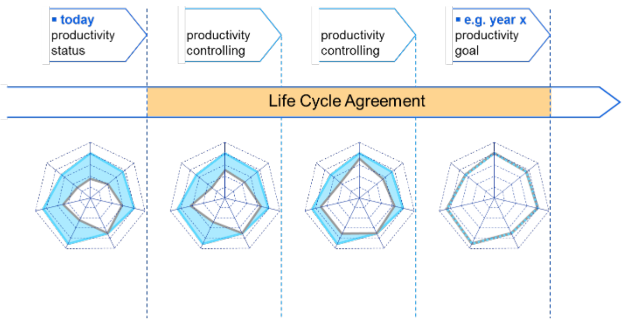

Figure 5 - Figure 4. Transparent way of productivity controlling

Guaranteed costs prevent any unpleasant surprises for the duration of the contract and allow operators to draw up budgetary plans for the entire life cycle of their plant (see figure 6).

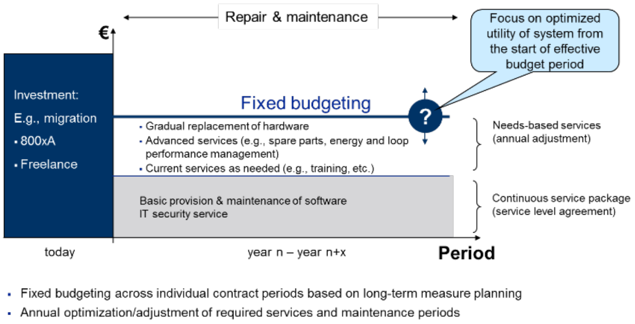

Figure 6 - Long-term agreements with fixed budgets

This foresighted planning approach allows the control systems to be kept up-to-date at all times and maximizes the benefit which the operator gains from the plant by coordinating all necessary measures in the long term. [8,9] Planning with Life Cycle Budgets reduces costs by 10 to 30 % over the agreed contractual term compared to classic care schemes.

Special trained life cycle managers are responsible for indexing customers' plants. At first they record the actual plant status on the customer's premises. In order to allow detailed visualization, the analysis of the strengths, weaknesses or productivity risks is subdivided into a total of seven axes.

This actual status record then provides the basis for a list of recommendations for a plant-specific target profile taking the company's individual objectives into account. This profile is prepared by consulting specialists from the manufacturer, by using the information they received and their many years' experience, and it is based on the evaluation of the customer's long-term objectives for plant operation. The necessary measures are also prioritized and arranged on a time axis. As a result of the "plant indexing" process, customers are provided with a detailed analysis of the strengths and weaknesses of their process control system and therefore the productivity status of their plant. During a second consultation which takes place on customer's premises, the results of the analysis as well as any recommendations are presented.

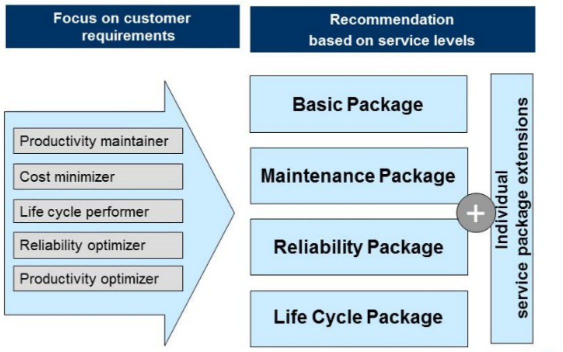

Figure 7 - Proactive service level management

Specific packages of measures are then agreed with the customer. These are developed further during subsequent discussions and then used as a basis for offering specific services (see figure 7).

3.5 Lessons learnt from the Index

Experience shows that life cycle planning is essential where users have ambitious plans to achieve constant increases in productivity. Previous indexing has revealed that such dynamic companies invariably use life cycle management in order to realize their full productivity potential. These plant operators have long-term approaches when it comes to automation planning and make particular use of modern IT systems and tools in order to develop further improvements based on the production data collected. In most cases, this is done by setting up effective control loops within the company organization. Faults and potential for improvement are analysed and implemented thoroughly in ongoing improvement measures. Figure 8 shows, based on the overall evaluation of 200 performed indexes the typology of plant operators from chemical, metals, minerals oil& gas and glass industries based on their business targets. It could be observed that especially in chemical plants operators are trending towards productivity increases and life cycle performance.

Nevertheless, life cycle management is also becoming increasingly important for those companies which are focused on maintaining productivity. Unlike ambitious companies, this group of users is primarily concerned with maintaining the status quo of their system components in the long term.

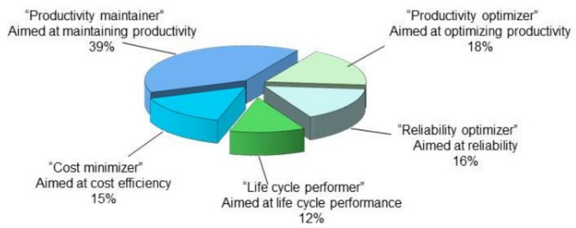

Figure 8 - Plant operator types [9]

Life cycle extension agreements ensure long-term support (spare parts, software maintenance and service level) for the products already used including any preventive and emergency strategies which may be necessary (see figure 9).

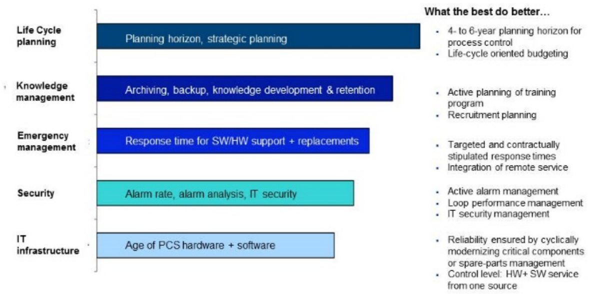

Figure 9 - TOP 5 list of hidden potentials [10]

The first indexing projects have also shown that the companies' ambitious productivity objectives demand a much more extensive system maintenance. This is reflected in index values which are 30% higher than average. Almost all companies with major streamlining requirements operate their plants using up-to-date system technology and invest in failure prevention.

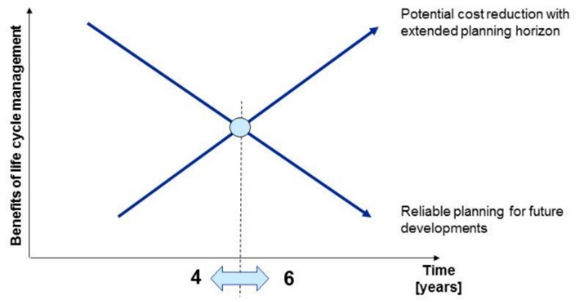

Figure 10 - Optimal planning horizon

The practical evaluation also showed that the best-in-class rely on a four up to six years planning horizon when it comes to the planning of a life cycle strategy (see figure 10). This seems to be the optimum between the desired potential of cost saving and a reliable planning horizon.

Accordingly, efficient production is achieved through active system maintenance and the use of state-of-the-art technology. Companies which are primarily interested in maintaining their productivity tend to use older system equipment and cover the risk of failures primarily by implementing extensive emergency strategies.

4 LIFE CYCLE EXCELLENCE DELIVERED WITH SERVICE

Today, a consequent life cycle management enables operators to realise far-reaching productivity potentials along the operation and to secure future-proofness and investment protection of their plants. The deep and total exploitation of such opportunities in automation serves as a central lever to consequently maximize benefits from high availability and productivity.

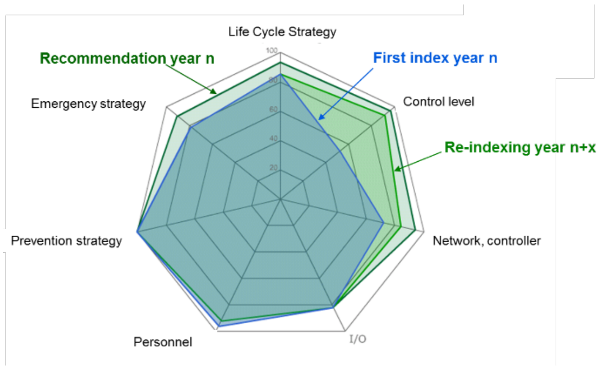

Figure 11 - Practical example of a re-index audit

Results from research show that over various levers in life cycle management more than 30% of potentials can be realized.. [3,11] Figure 11 shows a practical example of a re-index audit. The graph shows that the plant operator initiated some activities to raise the index score e.g. on the control and network level.

5 BENEFITS AND LESSONS LEARNT

The customer feedback has shown that the consulting approach with a life cycle index enables the company to execute a qualified consulting approach by a „best-in-class" benchmark.

Especially the benchmarking approach was of high interest to the customers and has led to a high „consulting demand". The indexing made it also possible to identify cross-sectoral plant profiles and typologies („index profiles").

For the company itself the index supported the ongoing service business and has secured the installed base business in a highly competitive market. Key factors for this were the structured visualisation of customers´ strength and weaknesses. This structured agenda served as a base for sales for future customer care and securing on-going contracts.

But the implementation of the index as a regular and on-going sales tool created also additional business. The identification of typical index profiles and statistics supported the sales of further services („All others have it? Then I wanna have it, too…").

The analysis of potential weaknesses discovered additional demand on customer´s side or was in many times the trigger to migrate to the latest technology.

In total - and maybe the biggest achievement with long lasting impact- the service department of the company was recognised as a trusted partner in life cycle management.

6 SUMMARY AND OUTLOOK

Process control systems nowadays can easily have a lifespan of more than 20 years – provided that they are looked after and maintained correctly. Thanks to the “Life Cycle Index”, operators can now for the first time record, assess and plan the productivity potential and risks of their control system installations in an objective manner. By a continuous indexing of the plants manufacturer and operator commonly take responsibility for the productivity of the plant. By this the manufacturer becomes a strategic production resource for the operator. A proactive service in return will ensure to meet long-term plant goals. This creates a long-lasting, value-driven partnership which is driven by life cycle service excellence.

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8 BIOGRAPHY

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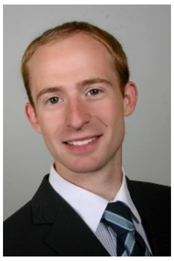

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A Roadmap towards Significant Customer Value in a Complex Product Environment

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Abstract
Three fundamental processes of an enterprise are development, operations and marketing. When a product or service (Knowledge Item) is introduced to a customer, a specific series of success events are triggered. These events are modelled by using a roadmap underpinned by environmental influences, key (specific) decisions as well as human interaction between different role players' involved in the life cycle of the product or service. Consequential phases of the engineering lifecycle drive an increasing maturity level of knowledge associated with the development item. A three-dimensional space is utilised to describe the knowledge attributes of the development item under discussion. This approach improves the success rate of a complex project by conceptualising premeditated (road mapped) tacit and explicit knowledge exchanges with the customers within the associated success events. A holistic roadmap towards realising customer value, and consequently the improved enterprise success, is discussed. The enabling contribution of human interaction factors towards the success are categorised and evaluated. Our understanding of the roadmap towards true customer value was augmented with applied studies in the areas of knowledge management, innovation, leadership, and other elements of the model. Project based case studies were conducted using a structured questionnaire sent to all knowledge workers with specific identified experience on the selected case studies. This resulted in a better understanding of dynamic, interdependent processes within the roadmap. This roadmap can be used to improve the probability of success of an enterprise by understanding the specific elements and their sensitivities towards the success event's outcome. These events can be manipulated to benefit the enterprise. It will enhance its competitive position as well as the success related with a specific project, thereby realizing a significant value proposition for the customer.

Keywords
Knowledge Management, Human aspects, Decision making.

1 THE CHALLENGE

This article presents some insights to address the following problem statement: Understanding the dominant combination of factors contributing to the success of a complex project (Lu [1]) throughout the different life cycle phases of the product, the enterprise and the market.

2 THE BROAD OUTLINE

These factors and their interrelationships are presented in the following Success Event Framework.

2.1 The Success Event Framework

A success event is defined as a series of premeditated (road mapped) tacit and explicit knowledge exchanges [2]. These contributes towards the ultimate success of a project and thus also that of the business. Examples of success events are:

- A **communication interaction** like a meeting, a letter, e-mail, or other interaction during work or social sessions with the customer.
- A **formal presentation** of a bid, a product description, contract negotiations as part of the acquisition life cycle
- **A formal design, program and contract revi**ews with the customer, i.e. milestones in the Acquisition Lifecycle
- A sincere, honest and speedy reaction towards **mitigation of a problem** or a perceived problem.
- An informal and formal presentation of in-process (**stage buy-off**) and the final product.
- The **interactions during the delivery of a service**.
- The **actual performance** of the deployed product against the expected performance.

Success is defined as the culmination of a series of such success events throughout the acquisition life cycle of the product that results in the best possible financial and strategic positioning of the project and the enterprise Exploiting:

- Various knowledge management models.

- Technology, product and enterprise life cycle models.
- Customer belief and value systems.
- Factors within the enterprise that the supplier can control or partially influence contributing towards competitiveness and innovation.
- **Human Interaction** consisting of leadership, relationships, wisdom (knowledgeable decision making) and corporate culture.

These factors and their interrelationships are presented in the following Success Event Framework.

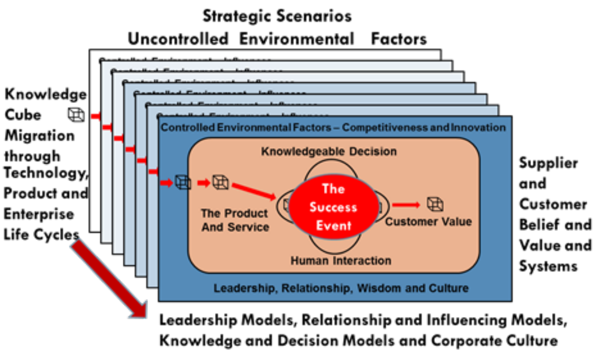

Figure 1 - Success Event Framework [2]

2.2 The Knowledge

Product knowledge attributes areadequately described using a three-dimensional space consisting of a structure, a functional description as well as the current and future level of potential design maturity. This three-dimensional space was previously described by Pretorius [3] as the Knowledge Cube Framework. In the same manner, the customer specifies required performance levels, as well as the time when the mature product design is required.

2.3 Related Life Cycles

Life Cycle Management is an imperative in successful enterprise engineering, Duflou [4]. The Success event life cycle management environment is guided by three life cycles i.e. Technology, Product, and Enterprise. The Technology Life Cycle starts with an Idea that develops into a qualified useable technology followed by exploitation, decline, as well as the termination or run-out of the specific technology. Exploitation of such technology is almost always performed by multiple competing enterprises [5]. The Product Life Cycle follows a similar start-up, growth, maturity and decline phased process. This feed the enterprise life cycle with a many to one relationship. I most enterprises exploit more than a single product, often or even multiple product range [6].

The Enterprise Life Cycle starts out with moderate growth in financial performance. After the initial success, it exhibits increased growth as subsequent successes are realised. In the operating phase where focus is on optimal return, the curve begins to level out. If renewal (innovation) is not appropriately induced at this point, decline will follow with subsequent demise of the enterprise [7]. The ability to recreate and innovate in the mature period is indeed a fundamental requirement for a sustainable enterprise.

2.4 The Market requirements and evaluation

The customer normally defines mandatory attributes as well as a weighted scale for the rest of the required functional performance for a specific project. Typically in an engineer-to-order project [8], the customer also contracts a future commitment of the product performance. This is normally defined in a performance matrix, against stated requirements and specified timeline. Alignment of the offered product's attributes is based on subjective and objective elements combined in the three-dimensional space against the customer requirement set. Competitive product analysis is also performed within this framework.

2.5 Competitiveness and Innovation

Innovation increasingly dominates the competitiveness arena. Transparent innovation management enables economic growth and sustainability of the enterprise and forms an inherent ingredient of success event management as defined by Seliger [9].

3 A ROADMAP TO PROJECT SIGNIFICANCE

In the compilation of the roadmap for success the following two domains were considered:

3.1 The Executables

This domain represents all the essential business processes starting with an idea and culminating in a successful customer value realisation. The executable business processes are analysed by considering their contribution within the areas of product, enterprise and market that in essence are the three focus areas of any enterprise introducing a new product to the market. Operational, tactical and strategic planning and executing horizons are exploited to add an element of order towards the roadmap for success.

The differentiation between enterprises is defined by the appropriate quality levels of the execution of these business areas in the nine-point matrix making up the executable domain. The executable factors of the roadmap to success are depicted in Figure 2 below:

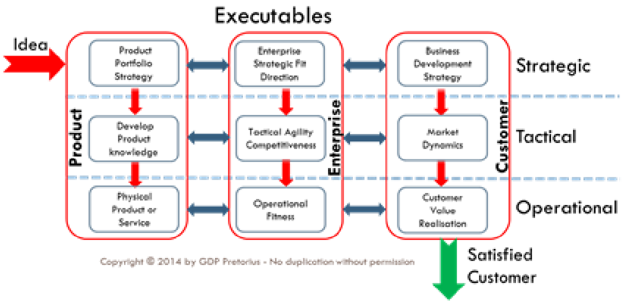

Figure 2 - The Executable Roadmap to Success.

3.1.1 *The Executable Processes*

By combining the business areas in a specific way the following six executable processes are defined in the roadmap to success.

Process 1: Strategic Planning

The process entails aligning and extending the company's product portfolio and the capabilities within the company and its strategic partners with the future market demand to obtain maximum significant value for the shareholders.

Process 2: Competitiveness Review

The process of understanding the competitor's products, their competitiveness and their tactical plan and comparing it to the company and its partners own products and competitiveness positions in order to define its own tactical (campaign) plans as related to specific opportunities or regions.

Process 3: Operational Management

The process of effectively and efficiently executing the operational tasks to deliver the expected customer value realization within the cost constraints of the contract.

Process 4: Project Management

The process of managing resources (internally and externally) to address the requirements during the execution of the current contract taking into account the continued change in the needs of the customers.

Process 5: Product Development

The process of acquiring and validating the knowledge attributes of a product.

Process 6: Business Development

The process of understanding the market trends, influencing the strategic plan, developing the customer relationships, managing the company's tactical response and keeping the order book filled.

3.2 The Enablers - The Human Interaction

In many instances, success or failure of the identified processes is significantly influenced by human interaction. Figure 3 presents key areas of important human interaction within the success event roadmap.

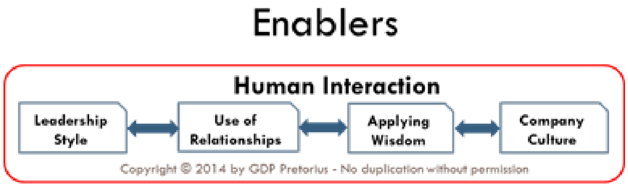

Figure 3 - The Enabler Roadmap to Success

3.2.1 *Leadership*

Ward [10], through the study of companies at different stages of the organization's lifecycle, concluded that there are unique challenges facing organizations and its leadership at each transition between the different stages. Consequently, it requires a significantly different changes in managerial and leadership skills to lead an organization at these different transitional periods. Hence, the Leadership Lifecycle with the Creator, Accelerator, Sustainer, Transformer and Terminator roles required for success.

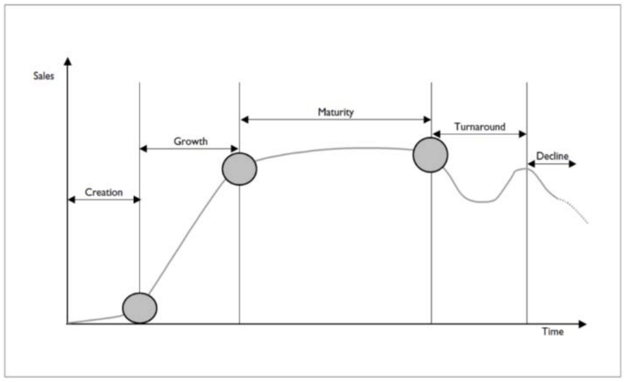

Figure 4 - Leadership Styles vs. Enterprise Phases[10]

3.2.2 *Relationships*

The human interaction is depicted by a relationship model by the, as yet to be published, work of Stiglingh [11].

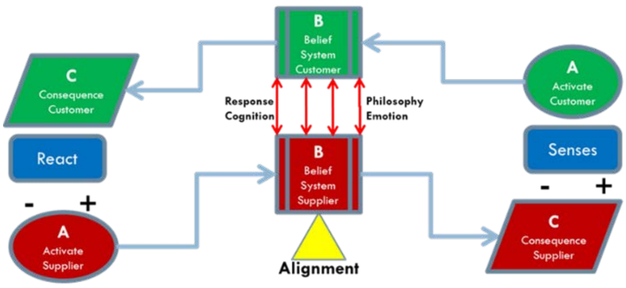

Figure 5 - The Influencing Framework

To obtain the best results from this model, it will be advantageous if the supplier and the customer's belief systems are closely aligned. The belief system is the actual set of precepts from which you live your daily life, those which govern your thoughts, words, and actions [12]. As no complete alignments between the belief systems of the customer as well as the supplier, at all levels, are realistically possible, one needs to focus on areas of miss-alignment that have the potential to turn a success event into a failure. From this model, it seems that a positive consequence must be sought through careful planning of the success event actions.

3.2.3 *Wisdom*

Management is defined as a series of decisions combined with supportive actions. Knowledge, on the other hand, exists as tacit knowledge within the people as well as explicit knowledge within the enterprise [13]. Knowledge Management is one of the key factors that drive competitiveness within an enterprise [14]. The making of enlightened decisions by combining good insight based on experience and one's own belief system, augmented by appropriate knowledge levels, gives rise to the concept of wisdom [15].

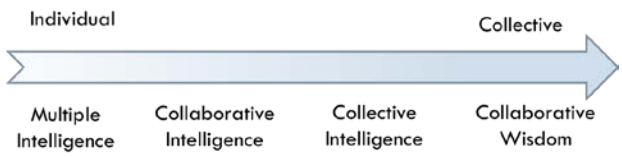

Figure 6 - Collective Wisdom Continuum[24]

3.2.4 *Organizational culture*

Organizational culture is the behaviour of humans within an organization and the meaning that people attach to those behaviours. Culture includes the organization's vision, values, norms, systems, symbols, language, assumptions, beliefs, and habits [16]. According to the literature, the business belief system comprises of the following four elements [17]:

1. Behavioural Performance, Action, Inaction – How people respond to what is happening.
2. Cognitions, Mind-sets, Clarity, Perceptions – How people think of what is happening.
3. Philosophy, Core Beliefs, Personal Values – The meaning people attach to what is happening.
4. Emotional Climate, Relationship Management, Emotional Information – How people feel about what is happening.

Figure 7 - The Cognitive Behavioural Theory Flower for Business

This industrial belief system manifests itself in different corporate culture forms like:

- **An Innovation Culture** stemming from the need for urgent renewal at the forefront of technologically based competition [18].
- **A learning-based culture** with the underlying premise of natural growth for an enterprise [19].
- **An empowerment culture** fuelled by requirement to expand and move from one phase into the next enterprise life cycle phase [20].
- **A prescribed, self-developed, corporate culture** as is evident in most of the big military multinational corporations required to establish their identity [21].

Although this breakdown compartmentalise specific cultures, the reality on the ground actually consists of a combination of the above with one or more taking the dominant role.

3.3 The Roadmap to Success

Interaction between Executable and Enabler Factors:

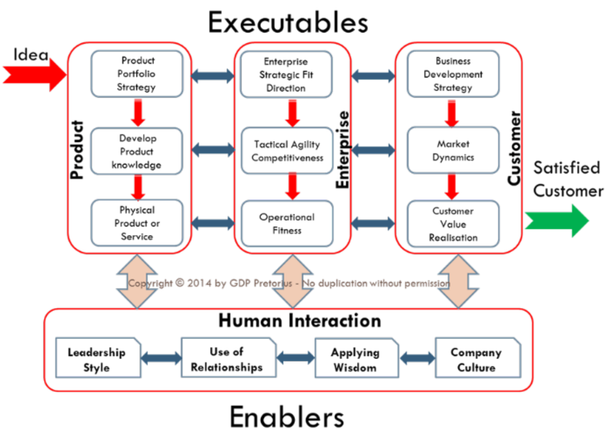

Figure 8 - The Roadmap to Success

The Success Event Roadmap will not be complete without the consideration of the different life cycles defined earlier and introduced into the roadmap as depicted in Figure 9.

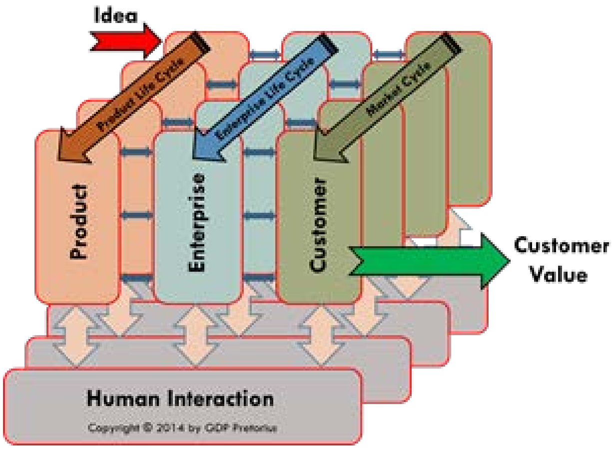

Figure 9 - The Roadmap to Success with Life Cycles

4 SUMMARY OF RESULTS

4.1 Introduction into the Case Studies

4.1.1 Case 1:

The supply of Light Protected Patrol Vehicles to the Swedish Defence Force. This case represents the creation, growth, mature and turn-around enterprise life cycle phases. Case 1 is a marginally successful project.

4.1.2 Case 2:

The support of the South African National Defence Force's fleet of logistic trucks in service. The mature phase is represented by this case. Case 2 is a stable but low contributing project.

4.1.3 Case 3:

The supply and upgrade of MRAP vehicles to the USA Department of Defence were conducted during the growth, mature and turn-around phases. Case 3 is an extremely successful project that realised high value for all stakeholders.

4.2 Comparative Analysis

The relative contribution towards the success of the enterprise (project) of the Enabling Factor's interaction with the Executable Factors was interrogated using a structured questionnaire. A total of 120 respondent's returns were received which represents 83% hit rate on the preselected list of potential respondents. Triangulation of the case studies' results as defined by Yin [22] was achieved by means of a work session with the company's executive team as well as the author's direct involvement in all of the cases during his 33 year career in the company.

4.3 Summary Results

4.3.1 Leadership

The confirmation of leadership style prevalent during the different enterprise phases, as defined by Ward [9], resulted in a close correlation overall. A remarkable close correlation in Case 1 was also prevalent where a lot of leadership focus was expanded in order achieve success as defined in Figure 10 below.

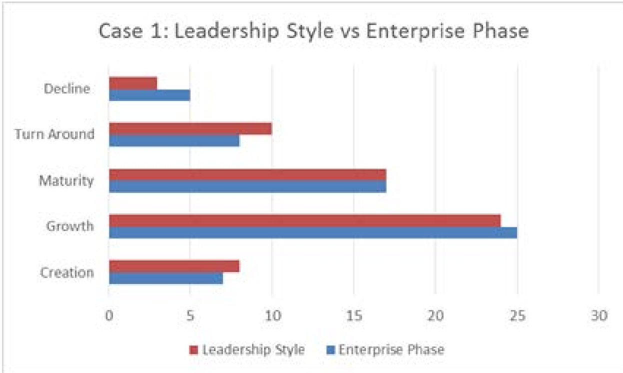

Figure 10 - Case 1 Leadership Style vs. Enterprise Phase

4.3.2 Relationship

A 5 point Likert scale [23] was used to obtain the opinion of the respondents in a series of questions regarding the contribution of the relationship factor. The summary results are shown in Figure 11 below. The results indicate most dominant agreement in case 3 where the relationship with the intermediary company, through which the sale was done, as well as the relationship with the US MoD was always on a very sound footing.

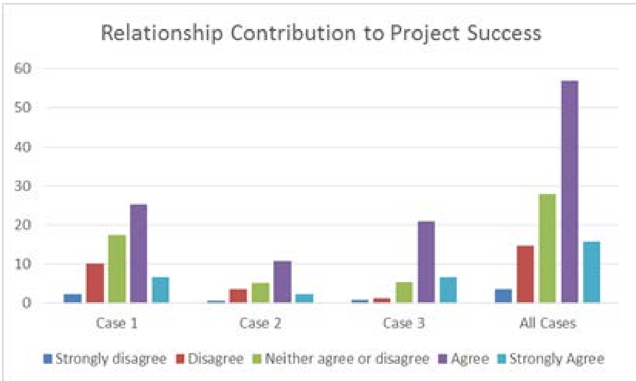

Figure 11 - Relationship Contribution

4.3.3 Wisdom

As depicted in figure 12 below the respondents agree that informed decision making in all cases were a major contributor towards their success.

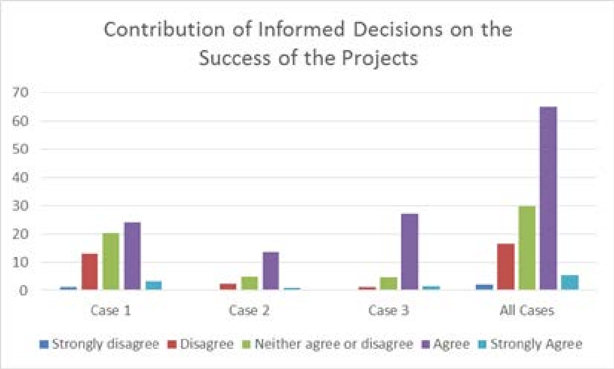

Figure 12 - Informed Decisions

In the case 2 and 3 results very little negative opinion regarding bad decisions are shown, however, as expected, the case 1 results do indicate a significant amount of respondents confirming that good decision making was not always prevalent in this marginally successful project.

4.3.4 Culture

The contribution of the different types of culture in the success of the projects results are shown in Figure 8. In the early development of the company, a significant focus was placed on developing the individual which is prevalent in the results shown where the learning-based culture is still dominant in its contribution to the success of the cases. Interesting to note is that the enforced corporate culture only had a neutral effect on the results of the company.

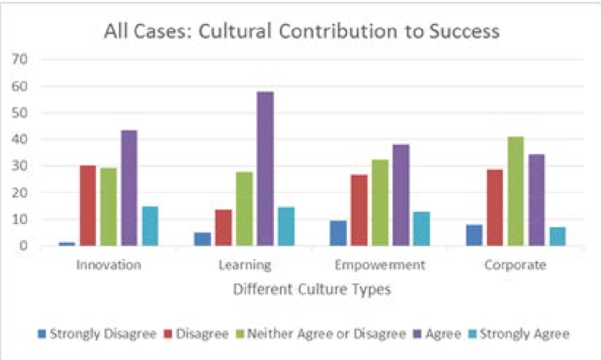

Figure 13 - Culture Contribution.

5 CONCLUSIONS

5.1 Interpretation of the Summary Results

It is concluded that four Enabler Areas do have a significant contribution towards the corporate success. However, the perceived contribution varies between the cases. The following detail observations are presented:

- The more leadership focus is required, the more defined correlation is demonstrated with the theoretical leadership style.
- In all cases, quality relationships are a prerequisite for success associated with a marked increase of the relationship contribution in the most successful project (case 3).
- The prevalence of bad decision-making results in a less successful project.
- Enforcing a corporate culture from the top does not necessarily contribute to the success of the company.

The Success Event Roadmap can be used to establish the potential contribution of any of the defined factors within the various processes. It also facilitates understanding of the contribution of the most appropriate factors in a specific scenario.

5.2 Additional research

Additional research should be considered in other phases of the Success Events Framework namely:

- The contribution and influence of the executable factors within their defined processes.
- The definition, grouping and contribution of the other controllable factors that drives competitiveness.
- The application of the Success Event Framework and Roadmap as an Enterprise Heath Check Tool.

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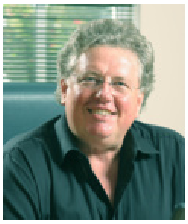
7 BIOGRAPHY

Gert Pretorius obtained his Master's degree in Engineering Management from the University of Pretoria. In 2009 he was appointed Vice President of New Product Development at BAE Systems in the USA. He currently serves as the Automotive Advisor to the CEO of NIMR Automotive LLC. In the UAE.



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Comparison of Experimental Data and Two Clear Sky Models

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Abstract

Solar energy is becoming a key player in manufacturing especially for off-grid applications such as community factories. Between the radiation emitted by the Sun and that absorbed on Earth, different phenomena take place. Many models were developed to tackle and explain these phenomena with varying levels of accuracy and complexity. Two commonly used models in most commercial simulation software such as ANSYS® Fluent® are the Fair Weather Condition and Theoretical Maximum Method. The aim of this paper is to investigate the accuracy of these models based on experimentally measured data. While these models assume a completely clear sky, the study is based on wet season. Global irradiance data acquired for different hours (9 o'clock, 12 o'clock and 15 o'clock) of the day was used. Results show good correlation between the average global irradiance for the Fair Weather Condition and the experimental values. The accuracy is more important for high solar elevation around 12 o'clock.

Keywords

CFD models, Fair Weather Condition, Solar energy, Solar irradiance, Theoretical Maximum Method

1 INTRODUCTION

The Sun is a star located 1.496 × 10^8 km from the Earth [1] and is the source of most of the energy on the Earth. The difference in energy emitted from the Sun and that received on the surface of the Earth is caused by a number modifying parameters. These range from reflection on the outer fringes of the atmosphere to absorption by atmospheric particles (dust, moisture). These factors have to be studied to understand how prediction models can be developed to estimate the component of the Sun's radiation that will reach the surface of the Earth and hence, allow modelling of the effect of radiation devices on the surface of the Earth. At the University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg, South Africa, experimental data has been measured for global radiations over different periods of time. For this data to be applied to simulation, it is important to understand the accuracy of the solar calculators implemented in various computation fluid dynamics (CFD) packages. The main aim of this study is to compare these experimental results with two prediction models that are implemented in ANSYS® Fluent® release 16.0 [2]. The two models considered were the Fair Weather Conditions and the Theoretical Maximum Method. In addition, the quality of the data was evaluated in an attempt to establish a correlation between the experimental and model results. The results of this analysis would be used in the development of a solar dryer for drying biomass briquettes and agricultural produce such as fruits. This solution is implemented in a container based factory that is currently under development.

2 SOLAR RADIATION AND THEORETICAL BACKGROUND

The Sun, at a distance of 1.496 10^8 km from the Earth, emits electromagnetic waves due to the chemo-thermal agitation on its surface. The temperature on the surface of the Sun, also called photosphere, lies between 4000 and 6000 K, but can be assumed to be at 5777 K for purposes of black body radiation studies [1], [3]. These electromagnetic waves are characterized by their frequency, period and wavelength. The latter is commonly used to represent the distribution of the solar electromagnetic spectrum ranging from 0.001 nm (gamma γ) to about more than 1 km (radio wave). The integration of the light spectrum over the entire range of extra-terrestrial wavelengths gives the solar constant determined to be 1367 W/m² and depends on three parameters [4]: the temperature of Sun, the size of the Sun and the distance between the Sun and the Earth. In addition, this constant can change during the year due to the Earth's orbit around the Sun which is on an elliptical path. Thus, the solar constant can change by around ± 3.3% in a year.

When the extra-terrestrial solar radiation arrives on the Earth's atmosphere, a fraction is reflected back into space and the other part will pass through the atmosphere. Of the component that penetrates the atmosphere, two phenomena appear due to particles in the atmosphere. The radiation is either scattered or absorbed. The first is the deviation of electromagnetic waves when it meets an atmospheric particle and this depends mainly on the size of the particle. The principal consequence of this is the decomposition into direct and diffuse components. The second is the absorption properties of molecules which absorb part of this radiation [1]. Then, there is also need to take into account the optical depth of the air mass which depends on two parameters: the geographical altitude and the zenith angle (θ_z). For the simple case, the latter parameter is taken into account through the simple Air Mass (AM) equation [3] i.e.:

$$AM = \frac{1}{\cos\theta_z} \tag{1}$$

After all the previously described phenomena that alter the incident radiation, around 52% of the radiation reaches the Earth [4, 1]. The irradiance (E) represents the flux density of incoming solar radiation on a unitary surface on the Earth perpendicular to the solar rays. From an energy point of view, 95% of solar energy is contained in the 0.3-2.4 microns band which contains the visible and infrared radiation [1].

3 EXPERIMENTAL AND MODELLING PROCEDURE

3.1 Aim of Experiments

The measurements were conducted as part of the development and performance monitoring of a biomass briquette dyer. The aim was therefore to quantify the amount of solar energy incident on the solar dryer flat plate collector.

3.2 Experimental Procedure

Global radiation was measured using a pyranometer in which the radiant energy is absorbed by a blackened surface whose temperature rise is captured by a thermopile. The resultant temperature change is measured as a potential difference (PD). The PD generated due to temperature change was recorded using a multi-meter and was then converted to irradiance.

The experimental data for a site in Johannesburg, South Africa was collected by Bloem [5] and Ragalavhanda [6] at the University of Johannesburg, Auckland Park Kingsway Campus in Johannesburg, South Africa. The location has the following global position system (GPS) coordinates:

- Latitude : -26°,11' S
- Longitude : 28°,00' E
- Time zone : GMT + 2 hours

The pyranometer "Second class" (16103.3) from Lambrecht used was calibrated in accordance to ISO 9847 standard [7]. The settings of the pyranometer have a sensitivity of 7-25 μV/(W/m²), a directional error of ± 25 W/m² and a measuring wavelength range of 285-3000 nm. The measurements were made every 15 minutes on a horizontal surface.

The data from Reunion Island was recorded automatically every minute to provide data for a different location and other parameters such as wind speed, relative humidity, ambient temperature, rainfall etc. The measurement location was at Saint-Pierre IUT on the Reunion Island, France with GPS coordinates:

- Latitude : -21°,20' S
- Longitude : 55°,29'' E
- Time zone : GMT + 4 hours

The pyranometer "Second class" (16103.3) from Lambrecht was also used and was calibrated in accordance to ISO 9060 [8] standard. The settings of the pyranometer have a sensitivity of 7-14μV/ (W/m²), a directional response error of 10 W/m² and a measuring wavelength range of 285-2800 nm. The measurements were made at an interval of one minute on a horizontal surface.

3.3 Modelling Data

3.3.1 Solar calculator

For the modelling data, ANSYS® Fluent® software release 16.0 [2] was used to calculate solar irradiance for clear sky with two methods i.e. Fair Weather Conditions and Theoretical Maximum Method. The first is based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) method [8]. The second comes from the National Renewable Energy Laboratory (NREL) method. Note that cloud cover is modelled through a cloudiness coefficient between 0 and 1 defined by the user (for most simulations, it is set to 1). The inputs for both models are common to experimental localisation, namely global position (longitude, latitude and time zone), simulation time (start and duration if transient), the mesh orientation, solar irradiation method and the sunshine factor [2]. The main outputs that are calculated (eq. 2) are: the beam solar flux (E_b), the diffuse component (E_d) and the reflected component from the ground (E_r). The latter will not be considered here since the measurements are based on a horizontal surface. To understand the differences of these models, the authors will present the parameters to understand their limitations. The direct component (beam) of the radiation is calculated according to the method chosen while the diffuse component is obtained from the ASHRAE method in both cases. Finally the global radiation reaching a unit surface is given by:

$$E = E_b + E_d + E_r \tag{2}$$

The ASHRAE direct method (eq. 3) uses empirical coefficients (A, B), calculated in 1964 on the basis of atmospheric conditions defined by: 0.25cm NTP ozone, dust 200 particles /cm^3, water vapor content is between 0.795 to 2.8 cm for winter and summer respectively. According to [9], A is the apparent solar irradiation at air mass = 0, B is the atmospheric extinction coefficient which is the slope of direct normal irradiance as a function of air mass.

$$E_b = \frac{A}{e^{B.AM}} \quad (3)$$

The NREL direct method (eq. 4) uses a Solar Position and Intensity Code (Solspos) algorithm. S_{etrn} is the top of the atmosphere direct normal solar irradiance, corresponding to solar constant taking into account the Earth-Sun distance. $S_{unprime}$ is coefficient corresponding to a clearness index and is defined by [10] as the ratio of Earth's overall surface area over extra-terrestrial global irradiance.

$$E_b = S_{etrn}.S_{unprime} \quad (4)$$

The diffuse component is calculated according to the ASHRAE method for both methods (eq.5). An empirical coefficient C is used to connect the direct and diffuse components. The coefficient α corresponds to the tilt angle of the surface. It corresponds to a linear coefficient which is defined as the ratio of the total irradiance over the direct irradiation for a horizontal Earth surface.

empirical data while Theoretical Maximum Method uses the solar constant corrected by Earth radius vector. In practice, the latter is not used because it overestimates values of the actual conditions of sunshine [2]. Although, the ASHRAE method is used, the coefficients used are empirical as determined in 1964 in the United States (Mount Wilson and Washington) [1]. Thus, they don't consider the variation of local conditions (altitude, ozone concentration, water vapor concentration etc.) and time of the atmosphere (changes in industrial discharges, decreased ozone layer, aerosol concentration etc.). It follows that the coefficients are global and do not differentiate the respective influence of other phenomena.

Thus, for direct component, ASHRAE method specifies that an error can occur for specific conditions (clear weather and high humidity) that can result in errors up to 15% [8]. It recommends the use of a Clarity Index (C_n), equivalent to Sunprime, but which is not included in Ansys FLUENT software. The Fair Weather method is presented in the literature as simple, including only few parameters. To overcome these problems some authors have redefined the empirical coefficients for their locality [11, 12, 13]. Finally, some studies have compared different models for the global, diffuse and global radiation. These studies do not arrive at the same conclusion. Some of them find a good correlation with ASHRAE [1] and others conclude

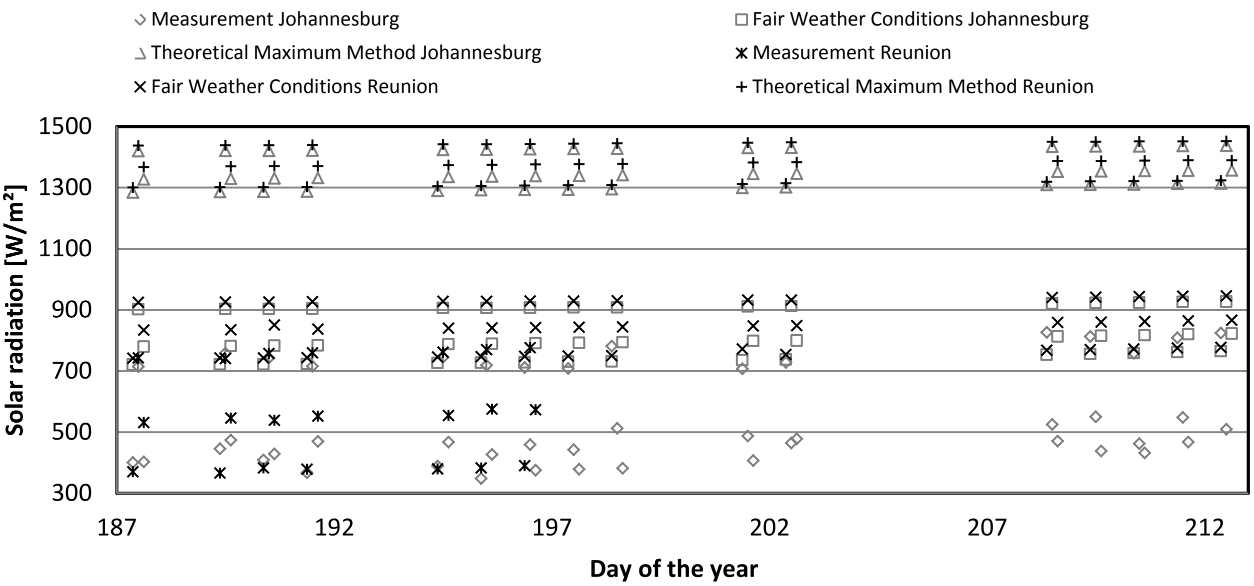

Figure 1 - Plot of solar irradiance from measurement and both models

$$E_d = C.E_{bn}\frac{1+\cos\alpha}{2} \quad (5)$$

The different methods to calculate the direct component and diffuse radiation incident on a unit area have been presented. The difference between the two methods for direct component is based on extra-terrestrial radiation, A and S_{etrn} on ASHRAE and NREL methods respectively. The first uses apparent solar constant which is calculated from

the diffuse component [2] can produces errors due to the simplicity of the method.

3.4 Experimental and Modelling Data

For the experimental data collected in the month of July 2015, three hours (legal time) were recorded each day and special note made for: 0900 hrs, 1200 hrs and 1500 hrs. However, due to weather changes (cloudy day) and data logging procedure followed (not automatically saving for Johannesburg), 15 and 7 days are available for the Johannesburg and

Reunion Island respectively. The lower value of Reunion Island is essentially due to the presence of more cloudy days.

The modelling data, using the solar calculator, was obtained by the addition of the direct and diffuse components based on the assumption of a completely clear sky, i.e. sunshine factor of 1. Moreover, it's assumed that the ground reflexion component and the influence of neighbouring buildings and structures i.e. microclimate are negligible.

The data are presented together (see Figure 1) bringing together for each site and time: the experimental data, The Fair Weather Condition data and the Theoretical Maximum Method data. Some outlier data are deleted due to error of acquisition or failure to meet clear sky model requirements. Thus 15 and 7 days are available for Johannesburg and Reunion Island respectively.

4 RESULTS

4.1 Method and Indicators

To evaluate the data and their quality the average and the standard deviation will be applied i.e. equations 6 and 7 respectively.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{6}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}} \tag{7}$$

In order to compare the experimental data and the predictions of the models, the Mean Bias Error (MBE) (eqn. 8) and the Root Mean Square Error (RMSE) (eqn. 9) which are statistical standards for assessing performance of solar radiation are used [15, 16]. In this case the error (e_i) will be considered as the difference between the model prediction and the experimental measurement for a given day. Finally, the two indicators are divided by the average of the reference measure i.e. to have the final result in percent:

$$MBE = \frac{1}{n\bar{m}}\sum_{i=1}^{n} e_i \tag{8}$$

$$RMSE = \frac{1}{\bar{m}}\sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \tag{9}$$

4.2 Results

The comparison is given in Table 1.

	Johannesburg		
Indicator	**Experiment**	**Fair weather**	**Maximum Theoretical**
Average	548.714	815.7	1355.9
σ	156.615	74.3	54.2
R^2		0.938	0.937
MBE		48.7	147.1
RMSE		51.1	99.8
	Reunion Island		
Indicator	**Experiment**	**Fair weather**	**Maximum Theoretical**
Average	562.952	846.4	1378.8
σ	159.512	74.0	56.4
R^2		0.987	0.997
MBE		50.3	144.9
RMSE		52.5	97.1

Table 1 - Statistical performance of the two models

The results show a relatively good correlation between the two models and the experimental data with a better coefficient of correlation for the Reunion Island data. This is explained by the higher source of error in the South African site due to manual recording of data and reflective surfaces i.e. buildings close by. However, the MBE and RMSE show an important difference of value between the measurement and the models for the two places and especially for the Maximum Theoretical Method.

Globally, the difference between experiment value for the site, and the Maximum Theoretical Model are important. The errors committed for Johannesburg are between 67% and 78% for Fair Weather Condition. The errors committed for Johannesburg using Maximum Theoretical Model are more than 100% and thus reject the utilisation of this model for engineering applications.

At Johannesburg the average for solar radiation at 9 o'clock, 12 o'clock and 15 o'clock is found experimentally to be 412.21 W/m², 756.4 W/m² and 477.57 W/m² respectively. For the Reunion Island the experimental solar radiation average are 378.27 W/m², 758.0 W/m² and 552.57 W/m² for corresponding times respectively.

The standard deviations of the experimental data are both 40.57 W/m² and 44.05 W/m² for the site of Johannesburg. For the Reunion Island the standard deviation of the data are between 5.95 W/m² and 12.45 W/m². The higher standard deviation for Johannesburg can be explained by the human error during the recording while in Reunion Island the recording is done automatically. Furthermore, the site of measurement and especially the surrounding can have a significant impact on the measure and can introduce errors e.g. reflective surroundings.

The coefficient R^2 has the objective to show the correlation between the experimental data and the model predictions. The results in Table 1 show a value of 0.938 and 0.937 for Johannesburg and 0.987 and 0.997 for Reunion Island. It means the experimental value agrees with the two models for global data. The results per hour are less impressive with a coefficient between 0.412 and 0.535 for Johannesburg and between 0.597 and 0.923 for Reunion Island.

The errors between each model and the experimental data are taking into account by the MBE and RMSE. The best accuracy for the different hours is for 12 o'clock where the MBE and RMSE is equal to 20.5 % and 23.12 % for Johannesburg and Reunion Island respectively by comparing experimental and Fair Weather Condition. The difference between the data and the Maximum Theoretical Method are too large to be considered for engineering applications.

The results per hour i.e. 9, 12 and 15 o'clock show better accuracy for high solar elevation meaning 12 o'clock. This is due to the increasing scattering with the longer transmission path of the solar radiation in the atmosphere during the off noon times.

5 CONCLUSION

The objective of this study was to demonstrate the accuracy of solar radiation models in modelling performance of solar dryers to be implemented in community factories. Indeed, between the radiation emmitted by the Sun and the radiation reaching the Earth different phenomena occur. Different models are availble which differ by the number of input parameters required and their complexity. The simplicity of these models can be accepted if the accuracy is also acceptable. If this is achievable, significant amount of time will be saved in developing the model to study and optimise the performance of these solar dryers.

This study has compared the accuracy of two models i.e. Fair Weather Condition and Theoretical Maximum Method in predicting experimentally measured solar irradiance acquired at University of Johannesburg and at Reunion Island University. The results show a similar behaviour for both models and the experiment data. However, the accuracy of both models is compromised for example around 9 o'clock and 15 o'clock. For higher elevation, the accuracy for Fair Weather condition increases and is found to be around 20.5 % and 23.12 % for Johannesburg and Reunion Island respectively.

The Theoretical Maximum Method shows significant difference with experiment data for the two sites and hence, must be avoided for manufacturing/ engineering application.

It is recommended that further studies be conducted by increasing the amount of data by conducting more measurements more time during the year. The summer studies can also be interesting to see the importance of the solar elevation to these results. Finally, the Fair Weather Condition possesses empirical coefficients calculated in America, and could be calculated for Johannesburg using experimental data.

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7 BIOGRAPHY

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Servo-Press Technology – a Contribution to Energy Efficiency

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Abstract
In the last decade, a new generation of servo-presses has been the focus in the production of deep-drawing components and forgings. This phenomenon has been advanced due to the requirements of even higher flexibility and more reduction of energy cost. Thus, the development of adequate drive technology was one essential precondition. Furthermore, systems had to be developed in order to supply the electrical energy. This contribution will present the connection between the drive systems for presses and the influence on energy consumption. Moreover, this relationship is also reflected in the technological requirements concerning the machine system.

Keywords
Energy consumption, cushion technology, standby circuit

1 MOTIVATION

Due to international competition, operators of press plants are forced to use resources efficiently. This is especially true for the total energy requirements and the energy distribution. Investigations are known that demonstrate energy balances in press plants and saving potentials regarding energy consumption in specific areas. In this context forming machines, e.g. as shown in Figure 1, play an important role, since they consume the largest amount of energy. If the relation of the forming machine is compared to the finally produced sheet metal part, it can be assumed that a large part of the energy consumption is required for moving masses or for rotary inertia – not for realizing the part. Due to the high investment cost of forming plants, the most important objective is economic operation. The highest priority is currently placed on the output power of the plant at high plant availability. Due to increasing energy cost, energy as a resource is playing an ever greater role in evaluating plant efficiency.

Concerning the further development of forming machines, the trend is basically driven by technology. The focus lies on an increase in output power, considering higher quality requirements for both, conventional sheet metal forming but also hot forming. By using servo motors as main drives of mechanical forming machines, a variable design of the ram transmission function can be realized. The approach results from an adapted motion profile with increasing speeds in the areas without applied technology, and in the technological stages speed adjustments according to the technological boundary conditions. This optimization of the motion profile can significantly increase the output power. Furthermore, assembly groups with high energy losses (clutch/brake combination) are saved by using the direct drive with torque motors.

Figure 1 - Modern servo-press line.

The objective resulted from the global approach to reduce energy consumption during the forming process. This requires detailed knowledge of the energy consumptions and standardizing them appropriately in order to draw a comparison of various plants and to derive significant points of focus for methods to reduce energy consumption [1].

2 APPROACH

Measures for reducing energy consumption require knowledge of the real energy input during the forming process. In this case the total energy requirements have to be determined and individual significant assembly groups of the plant need to be investigated regarding their share of the total energy requirements. Moreover it is necessary to define an assessable variable of energy consumption. For this reason the specific energy per part or per stroke of the press was introduced.

Extensive series of measurements were conducted at several presses in order to detect energy consumption [1]. The objective of the measurement series was to obtain basic findings regarding the shares of energy consumption of the individual press functions, depending on various operating parameters. Operating parameters include, for example, pressing force, stroke rate, type of ram curves (full stroke with constant rotational speed of motor, full stroke with variable rotational speed of motor, oscillating stroke), drawing force and drawing depth. In addition, the shares of power input of the individual press aggregates were systematically determined during standstill of the plant in order to also detect possible saving potentials outside of the plant production times.

In modern servo-presses the current cushion technology also takes up a large share of the total energy consumption of the forming plant. By conducting several series of measurements, the system-related share of losses was analyzed for the applied cushion technology. It was demonstrated that this cushion technology provided considerable saving potential – by optimizing the hydraulic control with no other change in cushion technology, or by completely changing the active principle of the cushion.

3 RESULTS

3.1 Analyses of energy consumption

Investigations of measurement technology were conducted at various plants in order to determine the power input of the presses or of selected assembly groups for identifying the energy consumption depending on individual press functions and various operating parameters [1]. For this reason, sensors inside the machine were utilized as well as external measurement technology, determining electrical characteristic values such as active power, currents, voltages and mechanical factors such as paths or forces. Power input or energy requirements per stroke of the press were used as reference values. These analyses were used to derive basic statements on the energy requirements per stroke for various components, shares of energy consumption of different assembly groups and share of losses during the non-productive time of the plant.

The energy requirements of the specific assembly groups were determined for selected drawn parts at a first press of a servo-press line. For this purpose the machine was operated with idle motion and also with built-in tool. Measurements were taken of the active power of the drive motors, the cushion force and the paths of cushion and ram. At the same time, the energy requirements of the cushion aggregate were measured.

The focus of the investigations lay on analyzing the lost energy of the main drive and the cushion drive, depending on various process parameters such as stroke rate, pressing force and cushion force. Furthermore an evaluation was carried out regarding the influence of the integrated energy storage unit on the energy flow within the machine and on the network load.

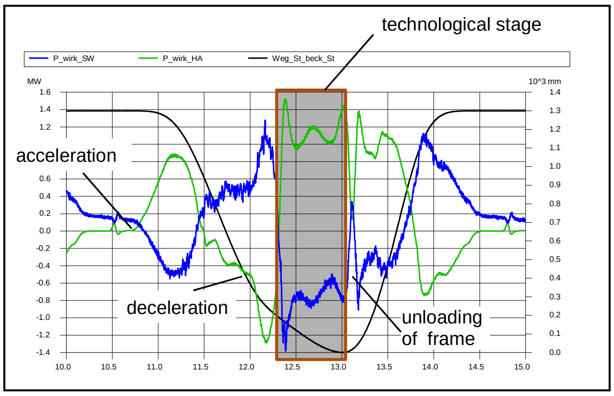

Figure 2 - Development of active power of main drive and energy storage unit of the press.

Figure 2 shows the real development of active power of the main drive of the machine (P_wirk_HA) during one working stroke. In addition, the energy flows from and to the integrated energy storage unit of the plant are presented (flywheel at the intermediate circuit, P_wirk_SW). The state-of-the-art of current servo-press lines includes individual energy supply systems for each press. This ensures that each press can always provide its peak power independently from the state and the load of the previous and the following systems. In order to reduce the network load these press systems are usually equipped with energy storage systems. Due to the high energy that has to be stored in each cycle only fly wheel storage units are used in large press lines. Further development of the energy management system of a press line is based on extending the DC intermediate circuit for the total press line while including several energy storage units for the complete network. This optimizes the individual energy flows to and from the consumers even more. Thus the energy losses are further reduced.

Due to the use of energy storage units, the energy is accumulated into the flywheel storage unit during the deceleration stage. During technological operation a large amount of the required energy is provided again from the storage unit. Thus the network load towards the outside is considerably reduced.

Figure 3 demonstrates that more than half the energy required by the main drive to form a large-scale drawn part is consumed by the cushion ("cushion displacement") due to the function of the machine. Additionally, the cushion analyses demonstrated that the energy input of the drawing aggregate was several times higher than the energy required from the press drives for the actual displacement. Without changing the established technological physical drawing concept, a considerable reduction in energy requirements can be achieved by optimizing the cushion hydraulics. Further energy saving potentials can be realized by changing the blank holder technology.

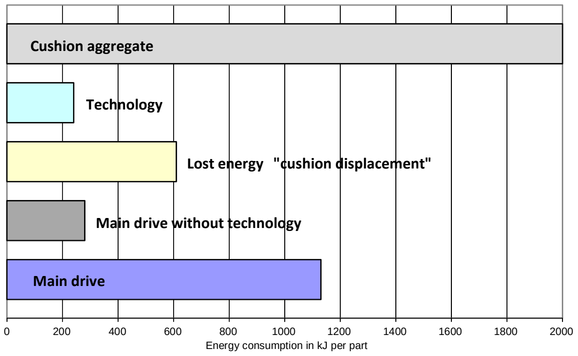

Figure 3 - Energy consumption at the machine, particularly for assembly groups.

Moreover, the analyses of power input show that modern servo-press lines have considerable power requirements at standstill. This phenomenon can mainly be associated with the high input power of the drive systems, the integrated energy storage units (flywheel systems), the hydraulic aggregates and the lubrication units.

Basically the power requirements at production downtimes can be drastically reduced by plant operators by manually or automatically switching off the systems mentioned above.

In a modern servo-press line the power input can be reduced from approx. 250 kW to 350 kW under operational conditions to 12 kW in standby mode (only controls are active, all other components are deactivated).

The following results or conclusions can be derived from the analyses of energy consumption:

- Approx. 1.5 kWh to 1.8 kWh is the amount of energy consumption when producing a large car body component.
- Of the above mentioned amount of energy consumption, approx. 0.8 – 1.0 kWh per part are related to the drawing stage.
- Up to 80% of the energy in the drawing stage is displacement energy or energy for operating the cushion aggregate.
- A comparable assessable variable was developed regarding energy consumption – calculation of the energy consumption is performed per part, thus the cost of energy is also applied per part (Figure 4).
- The energy consumption of the investigated machine basically results from the installed cushion concept.
- The cushion aggregate consumes the complete available power during cushion downtimes.
- The reduction of the energy required for displacing the cushion by the main drive can only take place by changing the generation of the blank holder force.

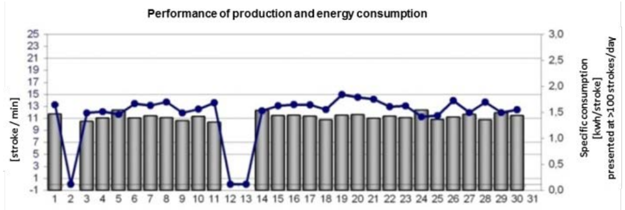

Figure 4 - Specific energy consumption at a forming plant [1].

3.2 Improving energy efficiency of production plants

It is necessary to examine the interdependency between energy input for shaping of the part and elasticities in the machine. Manufacturing of large-scale parts is problematic because of the associated deflection of the clamping surface of the die caused by the elasticities of the frame components. As a consequence problems occur when shaping the part in the center of the table. The machine operator compensates this error by increasing the pressing force, which means that more and more energy is accumulated into the spring effect of the machine frame. When using drives controlled by rotational speed, after passing through the bottom dead center, the spring effect of the frame is relaxed and the drive of the machine works against the resulting increase in rotational speed. Energy losses are the consequence. These losses can be compensated to some extent by a stiffer design of the machine frames (tables) combined with stationary blank holders (no cushion) or by a changed reference value curve of the drives (tolerating the increase in speed due to relaxing spring effect of the machine frame), see Figure 5. In order to quantify the effects FEM calculations were conducted at a forming machine, using various load scenarios. Furthermore, investigations were performed regarding energetically favorable reference value curves of servo-presses [1].

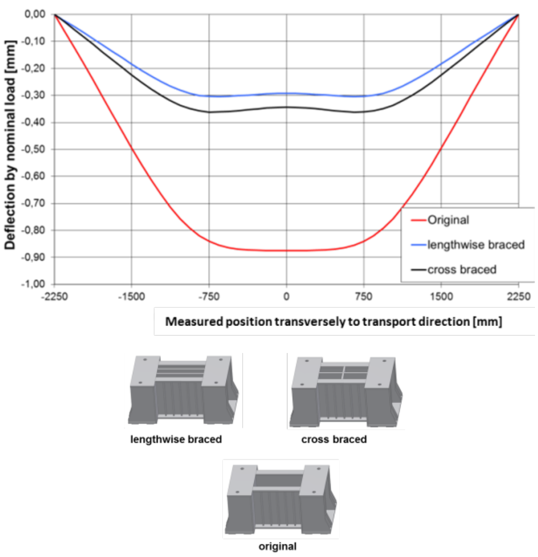

Figure 5 - Deflections of sliding table in various designs in the center of the table.

The analyses of energy consumption demonstrate that the cushion system holds significant potential for improving the energy utilization rate of the press. While maintaining the cushion technology applied today (valve controlled hydraulic displacer control), the energy requirements can already be considerably reduced by measures concerning design or control technology.

An even greater energy saving potential results from a change of the cushion technology. This requires a basic change of the functional principle of the ram actively displacing the holding-down device against the cushion force, which is associated with additional energy.

In the past, stationary blank holders were implemented as double-acting presses.

However, compared to single-acting presses with cushions, double-acting presses are very limited regarding their flexibility and output due to mechanic coupling of the drives of the blank holder ram and the drawing ram, and due to the geometrical design of the blank holder ram. It is possible to modify the technology of stationary blank holders of machines by further developing the drive technology using servo-electrical drives.

Ram drive and blank holder ram drive can both be arranged in the crown, below floor or also in a reciprocal design.

During one stroke the drives are operated synchronous or by a relative movement caused by the process. This implies the use of servo drives for the ram drive or the blank holder drive. Due to the high closing or opening speed of the ram, crank drives or link drives are preferred (Figure 6).

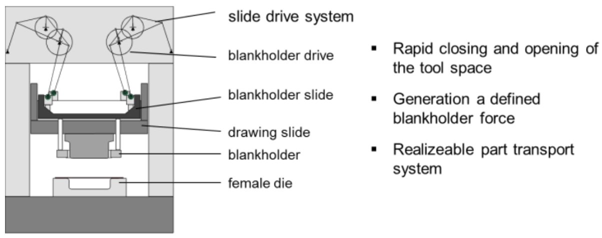

Figure 6 - Drive variants for stationary blank holders.

After the blank holder ram makes contact with the die, the drawing ram forms the part. During this operation the blank holder ram rests on the die. The specific requirements were determined for this variant. Based on these requirements, functional principles were derived and functional processes were developed. Then the drive (motors, gear) of a machine was designed as an example and also kinetostatically simulated (Figure 7).

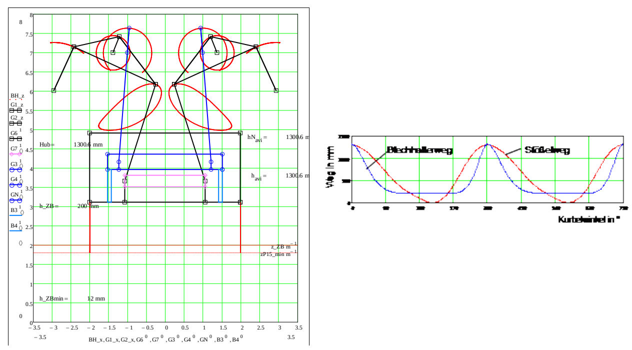

Figure 7 - Simulation of the kinematic processes of the drawing ram drive or the blank holder ram drive.

In addition to the theoretical considerations for realizing a stationary blank holder, drawings were prepared for a demonstrating unit which was constructed to prove the effects of energy saving when using this technology [1]. In order to reduce the expenditure for equipment technology, an independent blank holder unit was designed and then built into the working space of a press. The blank holder unit has a modular design and can be operated with various tools.

Two spindle drives are mounted to a base plate that is attached to the press table. These two spindle drives move the blank holder plate upwards and downwards. The punch is located at the press ram (Figure 8). The tool is opened and a blank is put onto the die. The blank holder passes onto the blank and clamps it against the die by applying a specific preset holding force. Then the punch shapes the part with the drawing ram.

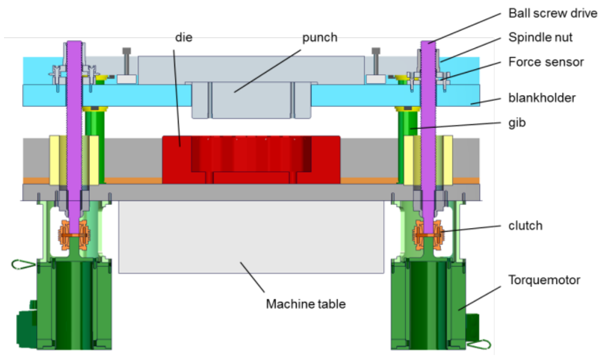

Figure 8 - Principle of a stationary blank holder.

It became clear that the required energy for the blank holder could be considerably reduced compared to the conventional cushion with displacers (ratio 1:7). This does not include the required energy of the aggregate of the conventional cushion.

Further research dealt with the interdependency of the drive of the stationary blank holder and the tool design [1]. In order to gain the users' acceptance for the innovative press technology it is essential to use tool systems of today as a basis.

Various variants were investigated for integrating the required functional assembly groups in order to construct a real drawing tool. An appropriate variant seems to feature assembly groups that do not have to be integrated into the tool directly, but can be used universally for various tools.

Figure 2 clearly shows the discontinuous power requirements of the main press drive outside the technological stage.

When considering energy it is advantageous to apply a constant load on the motor at least outside of the technology stage. This can be realized by a rotational speed profile of the drive with optimal energy. Due to the kinematics of the secondary gear the ram is accelerated or decelerated during the motion. Under ideal conditions (frictionless) the energy flows from the rotatory drive elements to the ram moving translationally and vice versa. If the machine runs at a constant rotational speed at the drive, the ram has to be accelerated and decelerated during the downwards movement, which leads to the energy flows presented in Figure 2.

If the system-related energy flows during the ram movement are exploited considering the ratio of the rotatory and translational inertia, the machine can be operated with constant drive power. However, this requires changing the standard of the reference value for rotational speed (Figure 9).

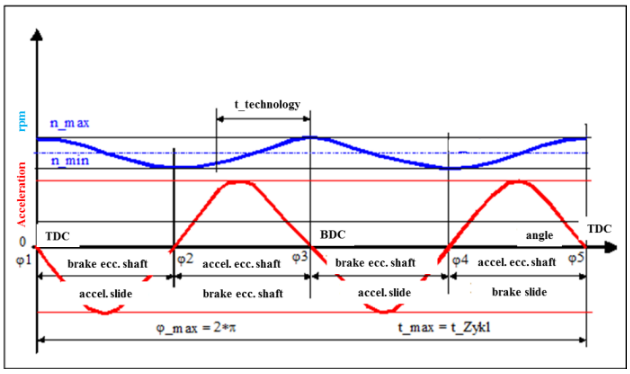

Figure 9 - Principle of rotational speed profile with optimal energy for an eccentric press.

Further potentials for optimizing the energy requirements by adjusting the curve of the reference value for rotational speed include "energy recovery" from the process or the tool (gas-pressurized springs) or unloading of the press frame at the beginning of the return stroke.

4 SUMMARY AND OUTLOOK

The technological possibilities to improve the energy utilization rate can be summarized by the following facts:

- The energy consumption of a modern press line or cross bar press with conventional hydraulic cushion technology is approx. 1.5 – 1.8 kWh per part in the manufacturing of car body components.
- Of the above mentioned amount of energy consumption, approx. 0.8 – 1.0 kWh per part are related to the first stage (drawing stage).
- Up to 80% of the energy in the drawing stage is displacement energy or energy for operating the cushion aggregate.

Significant factors for improving efficiency of forming machines include energy saving cushions, intelligent standby circuits and break circuits, the shared DC bus in servo-press lines and the use of a stationary blank holder.

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6 BIOGRAPHY

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Learning Factories Qualify SMEs to Operate a Smart Factory

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Abstract
Learning factories have been developed to impart substantial knowledge about improvement processes and methods to students and especially industrial participants within a real-world manufacturing environment. A new concept in the LPS Learning Factory has been developed to practically demonstrate how to operate a smart factory in Industry 4.0. Thus, especially SMEs are enabled to implement innovative ideas within their own companies.
The learning factory workshops base on the results of three Industry 4.0 research projects: “SOPHIE”, “APPsist” and “DigiLernPro”.

Keywords
Learning Factory, Industry 4.0, Smart Factory

1 INTRODUCTION

In order to increase competition on a global scale, manufacturing companies depend on well trained and educated employees who are able to handle the increasing complexity of production systems. To reach this aim, it is necessary to introduce innovative learning concepts [1].

Balancing different concepts, one finds learning factories to be especially adequate in this context because the transfer of knowledge from the trainings to the participants' own companies is facilitated by real production conditions [2].

The vast advantage of learning factories is the risk-free environment without pressure costs [3]. Participants have the opportunity to try out new methods within a real-world manufacturing system without interrupting the day-to-day business of the company [3]. This facilitates the application of learned content in their own workplace. While most learning factories in Germany concentrated on the field of lean management in the past, today's spectrum of topics has been expanded by the topics of production process, logistics, energy efficiency, design process, virtual/digital factory, change management, worker's participation and Industry 4.0 [4].

The future project of the German government called “Industry 4.0” does not just support the change in companies but also the further development of learning factories.

Industry 4.0 requires high standards in future learning factories. If the goal of Industry 4.0 is the complete connection of the company of tomorrow [5], it has to be mapped in the learning factory as well. Therefore, new learning concepts have to be developed. The present advantage of learning factories is the practical application of theoretical methods in a real factory (for example the value stream analysis). It will be a challenge to transfer this concept to Industry 4.0 learning factories in the future. It is necessary to develop new concepts which combine the sensitization, the demonstration and application.

2 INTRODUCTION OF THE LPS LEARNING FACTORY

The Learning Factory of the Chair of Production Systems covers four areas: lean management, resource efficiency, management and organization of work as well as the new field Industry 4.0. In spite of the diversity of these four areas, all of them are interlinked within the construct of the learning factory by the continuous use of real products, which are produced during a real production process.

In the new 4.0 Learning Factory we practically show how to manage a smart factory in Industry 4.0. Our aim is to show the transformation of the working environment, especially for SMEs. These may at best benefit from new profitable business models.

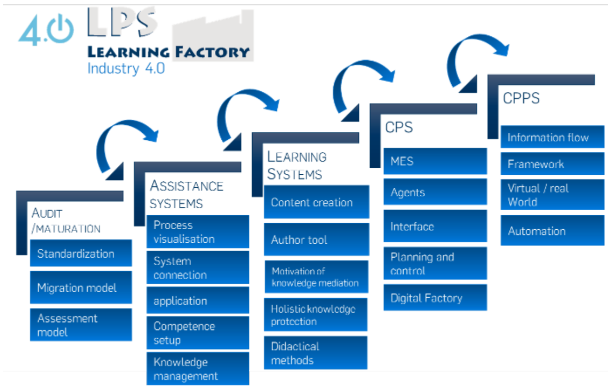

Figure 1 - Comprehensive transformation to an Industry 4.0 company

The didactical concept of the LPS Learning Factory mediates knowledge on different Industry 4.0 competence levels, which base on ongoing research projects. This concept is necessary to handle the comprehensive transformation schedule to an Industry 4.0 company (see Figure 1).

3 LEARNING FACTORY CONCEPT TO QUALIFY SMES

3.1 Transformation to an Industry 4.0 company

Industry 4.0 is a big challenge for companies. As already seen in the CIM-period, the short-term implementation of technical solutions will not lead to the expected outcome. The new technical possibilities constantly influence the organisation and the staff of a company. For this purpose, a general overview of all three design fields has to be created. For example, new job profiles for employees are a result of the new technological possibilities. The work in the production will become more complex and automated. The job profiles changes to a monitoring function for the employees. It also has an influence on the organizational structure of a company.

It emphasises that the change is very complex and that it cannot be implemented by the exclusive implementation of technical Industry 4.0 solutions successfully. Therefore, the transformation of production areas in companies has to be done systematically to Industry 4.0.

The transformation needs the expertise of different disciplines and will face companies with great challenges. It will especially face SMEs because they do not have the necessary resources to do the transformation. The question which status of Industry 4.0 is necessary will arise for every company. Decisions will be made by the companies' individual frameworks and feasibility studies.

SMEs have to be supported systematically in the transformation to an Industry 4.0 company. Every company has to develop an own schedule of how to create the design fields technology, organisation and staff. Therefore, a maturity model is necessary. It maps the actual Industry 4.0 status of the production and supports the transformation to a higher maturity level. An Industry 4.0 audit demonstrates in which status the company is. It also clarifies if technology, organisation and staff have the same development status. For instance, a company could have already installed a Manufacturing Execution System (MES) for their production control without adapting the organisation structure or without dedicated trainings for the employees. With the help of the maturity model, the transformation can be done systematically by the simultaneous consideration of technology, organisation and staff (see Figure 2).

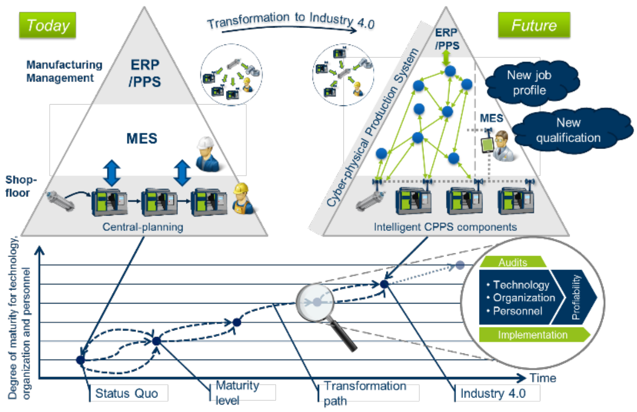

Figure 2 - Transformation to Industry 4.0

Learning factories play an important role for the mentioned transformation. On the one hand, they are a huge test and demonstration object and, on the other hand, they are the perfect learning environment for the employees. Here SMEs and their employees can experience how different Industry 4.0 statuses look like and how they affect technology, staff and organisation. With that it is possible to get an active experience of the maturity model in the learning factory.

The learning factory also provides possibilities for employees to get prepared for the new situation. Employees can be taught in new IT-systems, new organisation structures or new technologies by facing Industry 4.0 states in different scenarios. Through this, employees get familiarised and prepared with their new job profiles in a very practical and authentic way. Industry 4.0 offers a broad range of applications. In the LPS Learning Factory, especially the connection of production plants, the production control as well as the learning and assistant systems are considered. For this purpose, different learning scenarios are developed and described hereafter.

3.2 Interlinked production environment

The LPS Learning Factory is equipped with heterogenic machinery. Old and modern machines are connected to an MES, which collects data like operational state, resource usage, process and part quality, cycle times and many more. Continuous communication on shop floor level plays an important role to operate a smart factory.

Therefore, the LPS Learning Factory has the ideal environment to mediate the technical knowledge of a smart factory producing smart products in Industry 4.0.

3.3 Manufacturing control in Industry 4.0

Many companies operate their production control (e.g. planning of orders and employees) manually in Excel charts whereas advanced companies already use MES. So data from the production is collected which can be helpful in the process control. Nevertheless, the production control has to be done manually in MES. These examples already show two different maturity levels for the production control. In the framework of Industry 4.0, the production control should happen automatically. In this context, the usage of the digital factory is highly recommended in that a real-time connection between the digital and real factory is established. This happens by connecting MES, which contain actual data from the production and simulation programs. An information platform, which is realized by an agent system, serves as a hub and provides the necessary data and information for different target groups in the right context and in a role-relevant manner [6]. The application of this system is only successful if the integration and instruction together with the user starts at an early stage. Therefore, trainings and different user groups are created in the learning factory. Here the user gets an insight in the application of the system and gets to know the interfaces to other systems. Interactions with other systems and the effects of own actions can be seen directly in the real production environment of the learning factory.

3.4 Intelligent knowledge services for employees

Production companies face shorter product life cycles and an increasing product variety going along with high quality demands. The only chance to cope with this pressure is to support high-qualified employees, create innovative solutions and achieve constant excellent quality by a high degree of automation in production. Unfortunately, the complexity of the machines and tasks proceeds faster than the employees' skills to handle this complexity [7]. In the course of Industry 4.0, assistant systems are developed to help employees at their work on the shop floor level via cyber-physical systems. These systems have to meet different requirements:

- being context-sensitive for the individual needs of the employees
- offer the possibility to display all contents by different devices (tablet, augmented reality (AR)-glasses, smartwatch, smartphone, etc.)
- offer the possibility to provide different media as assistance (pictures, videos, text, AR-models, etc.)
- achieve learning effects for the user by the assistance
- provide tools to create assistant processes which have to be able to get connected with the actual infrastructure of the production (MES, PLC)

Besides the technical challenges that have to be faced, it is necessary to have a look at organisational aspects as well. In implementing new employee-relevant systems for the production, the worker's council has a big right of co-determination and information. Thus, these rights have to be considered for the development of assistant systems.

Against this background, it is important that employees and prospective engineers, during their studies, get to know about the new possibilities of assistant systems in the course of Industry 4.0. They also have to face technological and organisational possibilities but also difficulties about that concept. For this purpose, the LPS Learning Factory teaches participants of the "assistant seminar" in sectors like process visualisation, system connection, applications, competence development and knowledge management.

3.5 Learning on the shop floor by using digital learning scenarios

A key factor for securing the competitiveness of the German production industry is a continuous increase of productivity, flexibility and quality [8]. In addition, the worker is a central key success factor to technically innovative production solutions [9]. Especially in SMEs, workers have to be able to handle different machines and work stations, and serve different functions.

Furthermore, the complexity of work processes within the enterprise is increasing. Therefore, the machine operators require profound knowledge of the work process to manage these processes adequately [10].

Mobile digital media open up new possibilities to support employees in such ways that the described problems can be solved.

Focused on these facts, an intelligent learning system is going to be developed to support the machine operator individually. This learning content will be provided at the machine. The integration of the learning content in the intelligent knowledge system serves as a sustainable protection of every individual knowledge. This makes a new kind of learning possible. Besides the pure assistance of the employees on the machine, the focus of the research project "DigiLernPro" is on the learning or the sustainable protection of knowledge. Among retrieving already created data, the overarching goal is to motivate the employees, to see learning needs independently, create appropriate learning content and provide it to other employees. Because of this, employees are qualified to record the necessary process steps multi-modally with video, text or audio. Via an intelligent authoring tool, the presence of all necessary didactic methods is secured.

The developed methods and tools will be integrated in the learning factory within the scope of an own seminar block.

4 CONCLUSION

The complexity of Industry 4.0 leads to new technology, workplace and business model enhancements. Nevertheless, the role of the workers in the processes stays important. Therefore practical learning factory workshops have been developed to show the different Industry 4.0 maturity levels based on the three research projects “DigiLernPro”, “APPsist” and “SOPHIE”.

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The Learning Factory: A Didactic Platform for Knowledge Transfer in South Africa

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Abstract
During the first years of their employment, the graduates are a liability to industry. The employer goes an extra mile to bridge the gap between university-exiting and profitable employment of engineering graduates. Unfortunately some cannot take this risk. Given this scenario, this paper presents a learning factory approach as a platform for the application of knowledge so as to develop the required engineering competences in South African engineering graduates before they enter the labour market. It spells out the components of a Stellenbosch University Learning Factory geared towards production of engineering graduates with the required industrial skills. It elaborates on the didactics embedded in the learning factory environment, tailor-made to produce engineers who can productively contribute to the growth of the industry upon exiting the university.

Keywords
Learning factory, university graduates, competences, didactics, industry

1 INTRODUCTION

South Africa, as an emerging economy relies generally on the manufacturing sector for its growth. The industries which make this sector get their top-brass workers from the universities. Upon employing them, they find that some university graduates are still raw. They are unproductive during their early period of employment. Some of the graduates receive a cultural shock from the work environment in industry. They are simply a liability during the early phases of their employment, which at times deters some industries from promptly engaging university graduates upon exiting the university. Industry at times goes an extra mile to train them so that they reach a level on which they would be productive. However, not all industries are forth-coming to take up this burden. They would rather employ an experienced person than newly graduated university students. Therefore, the paper postulates a solution to this problem by presenting a Stellenbosch University Learning Factory (SULF) as a viable solution within the South African context. It reveals the competences required by industry on university graduates as they join the labour market. It also reveals some expected outcomes of Engineering Council of South Africa (ECSA) upon university graduates. Furthermore, the paper elaborates how the gap between industry and university may be mitigated by a learning factory approach in the educating of students.

2 LEARNING FACTORY APPROACH

Special skill requirements, demanded by industry and ECSA, require special use of appropriate teaching and learning methods, which meet specific training objectives in the fields of planning, implementation and optimization of production and manufacturing systems. Overally, there is a growing interest in practical and experiential learning environments. As a result, leading universities and colleges react by establishing learning factories [1-4].

These physical, operational factories usually cover the whole creation process of a product selected in accordance with didactical criteria and serve as exemplary and realistic hands-on learning environments. The concept of learning factories integrates self-directed and action-oriented learning in heterogeneous groups to encourage experiential knowledge, integrated into a formal didactical concept. This enables the trainer to address the intended competences systematically by guiding the learners through the processes necessary to acquire the intended knowledge and professional and/or vocational competencies. This symbiotic combination of the teaching of professional expertise, methods, individual competencies and soft skills [5, 6] may be achieved by combing traditional, instructor-based teaching methods with hands-on sessions held in teamwork to improve social and group work competencies. The tasks or problems students get confronted with are inspired by issues of high practical relevance and designed openly to avoid predefined solutions or approaches. By using mostly commercially available technologies in learning factories, a very authentic learning environment may be created, resulting in a highly immersive learning experience for the learners [7]. Additionally, high learning success is achieved by including the self-actions of and the interactions between the learners into the learning experience [4, 8].

Hence, the learning factory approach is seen as a didactical approach of learning which aims at producing graduates who have competences required in a real working environment [9]. These competences are acquired by students when exposed to real or simulated working environment during their university education [9].

2.1 Resources in a Learning factory environment

For a learning factory to produce the required calibre of graduates it should have a competent personnel (who may be lecturers, engineers and technicians). These should be able to interpret the requirements of industry and translate them into objectives of their specific modules and then create the appropriate content of study. They should be competent enough to communicate effectively those objectives to the students and be able to convey, using an appropriate methodology, the contents during the teaching period. A real work environment similar to an industrial set-up should be availed to university students to experiment in, as has been established in the case of Ruhr University, Darmstadt University [9] and Reutlingen University. The environment may be a physical room with the necessary equipment used in a real industrial set-up. In the case where such is not possible to achieve, a simulated environment may be a viable option. Videos of the real world of industry may also be used and video conference between students and engineers in their working environment as in the case of Greece [10].

2.2 Didactics in a learning factory

Learning involves mainly two parties: the students/ trainees and the educators/facilitators. The educators (in this case include lecturers, practising engineers, technologists and technicians) facilitate the learning of the students and industry's trainees in a learning environment. They facilitate in the sense that they expose the students and trainees to the learning factory modules (or subjects) and then allow them to methodologically apply the concepts in a hands-on session within a real industrial environment or simulated environment. In this learning factory environment, the lecturer does not use a teacher-centred approach to learning [11, but rather a student centred approach [11] in which the students or trainees empirically apply the knowledge obtained from the theoretical contents of the modules to a pseudo or real world environment at a level higher than simply doing an experiment in a laboratory. In some cases the students are given open-ended tasks without predefined solutions to allow them to develop the critical competences required in industry. Learning factories add flair to the learning environment by affording a "trial and error playing field" in which students and trainees may sharpen their competences by attempting to solve problems of industrial nature within the university premises [12].

3 SOUTH AFRICAN INDUSTRY AND ECSA REQUIREMENTS FOR LEARNING FACTORIES

3.1 ECSA Requirements

Generally the requirements of South African industry on university graduates are enshrined in the Engineering Council of South Africa (ECSA) outcomes and competences [13, 14]. These ECSA outcomes require university engineering graduates to have, among others, the following competences: problem solving capabilities, ability to apply scientific methods and tools to solve problems, capability to solve inter-disciplinary problems, capability to work independently, ability to work productively in teams, ability to solve as well as manage ambiguous and complex engineering problems [13, 14]. Although universities are trying to inculcate these competences in their students before existing the university, they are failing to adequately achieve this as revealed by some delegates who attended the South African Institute of Industrial Engineers Conference in 2013 (SAIIE 2013). The SAIIE 2013 delegates, during a discussion after an initial presentation on learning factory concepts, asserted that some engineering graduates are falling short as far as these competences are concerned, they even stated that some of them suffer a cultural shock, such that they are unproductive during the first period of their employment.

Currently, to improve the graduate engineers' competencies after leaving the university, South African companies have to train the graduates for some time to make them competent engineers. Normally the training is conducted under an ECSA registered mentor (a registered ECSA practising engineer). In some cases such training may take even more than two years. This paper proposes that the length of such training may be reduced if a learning factory approach is introduced at some point during the training of engineers.

3.2 Industry requirements for South African Learning Factories

In order to get the most benefit out of a Learning Factory; the taught competencies, processes and topics as well as the deployed infrastructure in the form of hard- and software have to be aligned with the requirements and needs of South African industry and academia. This alignment would at least partially bridge the mentioned gap between university and industry. Hence, approaching both parties before establishing a Learning Factory and developing learning modules is crucial.

3.2.1 Method

For this purpose, carrying out a workshop is an appropriate method of gathering special requirements for a South African Learning Factory. As in the case of the Stellenbosch University Learning Factory, such a workshop was carried out at a Conference of the International Academy for Production Engineering (CIRP) General Assembly which was held in Cape Town in 2015. In a four-hour workshop, participants from industry, academia and consulting were first introduced to the term 'Learning Factory' followed by an introduction into industrial engineering and its education in Learning Factories. On this theoretical base, two examples of Learning Factories were presented, the ESB Learning Factory of Reutlingen University and the Stellenbosch University Learning Factory which is currently in a developmental status. In order to tailor the Stellenbosch University Learning Factory to the needs of the local industry, specific requirements from industry were interrogated within a brainstorming session by posing three question:

- Question 1: What are the most relevant topics to be covered in the Learning Factory?
- Question 2: What processes should be presented in the Learning Factory?
- Question 3: What technologies are relevant; which IT-systems have to be integrated in the Learning Factory?

The workshop closed with a panel discussion with reference to the stated questions.

3.2.2 Main results of the workshop

Operations management methods, such as lean management, process optimisation and change management; and soft skills such as communication, team work, project management, intercultural and leadership skills, were among the most mentioned topics to be taught in Stellenbosch University Learning Factory. Besides those two learning areas, smart factories: including both the digital world and human/machine interface were also identified as relevant learning topics for a South African Learning Factory. A small number of participants mentioned also advanced design, product lifecycle management and networks as other topics to be included.

The most remarkable response to the question concerning processes which should be presented in the Learning Factory was that the entire product life-cylce, from the digital design and simulations stage through real production and assembly processes, including logistics and recycling, should be integrated in an Learning Factory environment by using cloud engineering and manufacturing exceution systems.

Concerning Information Technology (IT) and Technologies questions, answers were given in line with relevant processes which can be realised and supported by IT. Software for desiging and simualtion, software for planning and controlling manufacturing and production as well as software for allocating human resources and managing projects were recommended to be integrated in an South African Learning Factory environment.

3.2.3 Way forward

As a way forward, the knowledge gained from the workshop would be transferred into learning concepts that form the base for the development of learning modules for students and industry's participants who would be trained at the Stellenbosch University Learning Factory. Synthesising the outcomes of the learning factory through the internal enterprise architecture in Figure 1, the Stellenbosch University Learning Factory would in its initial phase cover the areas highlighted in yellow.

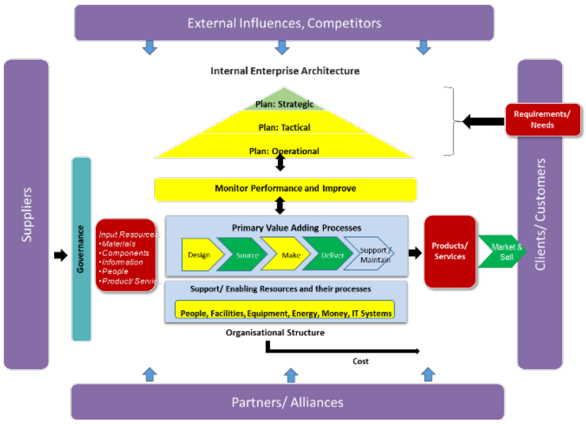

Figure 1 - Areas covered by Stellenbosch University Learning Factory

The Production Management modules would initially cover the operations management aspects (lean management, logistics, process optimisation and team work) the Quality Assurance module would cover aspects related to performance monitoring and improvement as well as product life cycle; Industrial ergonomics would cover aspects to do with the interaction among human resources, machines and the environment with respect to safety and ethical requirements. Manufacturing processes and Manufacturing systems would cover competences to do with design, production, assembly processes and simulation. Since a product is required in the morphology of a learning factory [15] alongside the learning modules, a collaboration with the Passenger Rail Agency of South Africa (PRASA) Research Chair has been initiated in which physical rail wagon models would be used in the Stellenbosch University Learning Factory.

With respect to the required ECSA competences [14] upon engineers, Table 1 shows a synthesis of some of the broad competencies engineering graduates are expected to have after undergoing Stellenbosch University Learning Factory environment.

Modules	Broad Competences
Production Management	Competency to manage complex engineering activities [14]
Manufacturing Processes and Manufacturing System	Competency to design and develop solutions to complex engineering problems [14]
Industrial Ergonomics	Competency to make ethical decisions [14] .
Quality assurance	Competency to meet standards expected independently in employment or practice [14]

Table 1- Module Competences

Figure 2 shows the educational pyramid, revealing the gap a learning factory fills in the production of engineering graduates who are better geared for the working environment in industry. In a university set-up, normally students firstly attend lectures, secondly they do tutorials, thirdly they may do experiments in laboratories, and fourthly they should then be exposed to the learning factory before they exist the university as indicated in Figure 2.

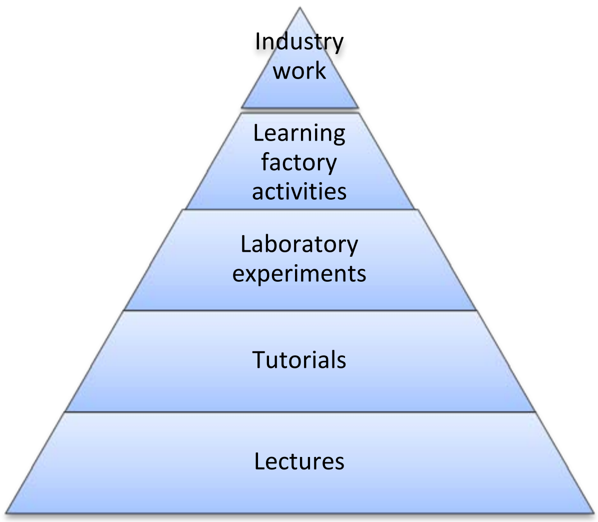

Figure 2- Learning factory - gap filling

In the learning factory environment, students attempt to solve a real world problem using a systematic, integrative approach applying various concepts they would have learnt in their learning-factory-tailor-made modules [12]. The problems could be holistic and complex in nature, not unidirectional – affording students various options as solutions, thereby necessitating the need to brainstorm, analysing the problem before synthesising a solution. This affords them the opportunity to work as a team in solving multi-directional and multi-disciplinary problems by logically applying various concepts learnt in their modules and outside the module as they would have researched [12]. It should be noted that the methodology used to solve the problem is not merely an experimental approach under normal laboratory conditions, but rather at a higher level, in which a logical, systematic and integrative approach is applied in solving a real-world complex problem [9].

4 CONCLUSIONS

In conclusion, a learning factory is an environment in which students are exposed to a real-world or simulated environment in which they tackle real-life problems which might be multi-directional and interdisciplinary in nature so that they develop industry-required competences by experientially exploring solutions. From the CIRP Learning Factory's workshop inputs, Stellenbosch University Learning Factory would provide a similar environment so that its engineering graduates would acquire competencies to design and develop solutions for complex engineering problems as well as to manage complex engineering activities. By offering tailor-made learning modules, delivered by a learning factory approach, the competence gap between student capabilities and the industry's as well as ECSA's expectations in a South African context can be mitigated.

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6 BIOGRAPHY

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Gamification: Teaching Within Learning Factories

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Abstract

Gamification, the use of game elements for non-gaming purposes, may just make a huge impact on education, a contribution the world in general and South Africa in particular, desperately needs. In today's fast-paced work environment, there is not only a severe skills shortage, but also a great need for graduates with practical knowledge - students that are not purely "book smart". Didactic teaching habits have created an education realm in which reciting facts is more often than not what gets students to pass. Learning factories are physical, operational factories that serve as exemplary and realistic hands-on learning environments and provide an important step towards more industry-prepared graduates. Top universities around the world are establishing such environments and are showing superb results. This paper explores the potential benefit of applying gamification in such a setting to enhance the learning environment even further, and provide opportunities for training otherwise difficult to teach topics, such as shop floor management.

Keywords

Gamification, learning factory, shop floor management

1 INTRODUCTION

"The direction in which education starts a man will determine his future in life." ~ Plato

In South Arica, approximately 50% of all students who start school, drop out before reaching matric [1], resulting in a real pass rate of only 36% for 2014. Of these high school graduates, less than 10% enrol for tertiary education, at which the average graduation rate of 15% [2] results in only 1 in every 100 youth in South Africa having an undergraduate degree. To add to the problem, business leaders have expressed concerns that graduates lack skills in problem solving and self-directed learning [3]. The direction in which we are sending our youth, is undeniably dismal. This paper aims to identify the problems and challenges faced in the current education system and analyses a new approach for learning as a possible solution.

2 HOW PEOPLE LEARN

2.1 Approaches to learning

[4] Discusses three distinctive approaches to learning, namely a surface-, strategic-, and deep approach. The surface approach relies on rote learning with the sole purpose of meeting the minimum course requirements. Students who are entirely outcome-orientated, motivated only by studying what is necessary to achieve high marks, follow the strategic approach to learning. A deep approach is followed by those students whose intent is to gain a deeper understanding of the material. The deep approach is the desired approach since only when a student understands the work material, can he/she apply it effectively in practice.

2.2 Principles of learning

According to [5], learning is based on the following four principles:

- Learning occurs in context.
- Learning is active.
- Learning is social.
- Learning is reflective.

These principles suggest that in order for learning to be successful, it should be based on real-world situations and contexts, involve the student actively, be provided in a social environment with interaction amongst students and educators as well as facilitate feedback that allows for reflection and reworking of ideas to improve understanding.

2.3 Learning theories

The main learning models discussed in the literature are the behaviourist-, cognitivist-, and constructivist learning theories. Cognitive learning environments are the traditional, purely theoretical and instructive ones [6], whereas behavioural methods incorporate purely practical training in an attempt to provide a more hands-on experience. Both theories are based on instruction, where the educator tells students what to learn or do. Over the past decade, there has been a shift in emphasis from behaviourist and cognitivist learning to a more learner-centred approach known as constructivism [3, 4]. Constructivism is based on the assumption that self-learning is developed when the student is actively engaged and attempts to gain an in-depth understanding of the environment [3]. The principles of constructivism are, active learner engagement, knowledge construction, collaboration and contextualisation [4]. These principles are directly aligned with the principles of learning discussed previously and would suggest that such an approach will result in the most successful knowledge transfer. The two most commonly discussed learning theories built on constructivism are Problem Based Learning (PBL) and Experiential Learning Theory (ELT).

2.3.1 Problem Based Learning

PBL is a learner-centred approach in which learning is driven by problems as opposed to facts or information [3]. It further allows for students to participate in a more real world context than traditional learning methods. PBL has been found to not only develop effective problem-solving skills, enhance the retention and application of knowledge, and provide opportunities for interdisciplinary skills and knowledge transfer, but also to promote active, lifelong learning and strengthen the recipient's motivation to learn [3].

2.3.2 Experiential Learning Theory

ELT is based on the idea that learning should be undertaken as a holistic process and not in terms of singular outcomes, as it has been done in the past [7]. An important distinction from PBL is that in ELT, learning is best facilitated by a process that includes feedback and allows for the reworking and relearning of ideas and knowledge, through experience. The learning process is modelled as a cycle where observations and reflections are based on actual experiences. These reflections lead to the abstract conceptualisation of knowledge, which in turn leads to active experimentation from which new experiences are drawn. [8] Describes ELT as a collaborative, hands-on, self-directed learning process that engages learners in a social learning environment.

Regardless of the method or theory, experts seem to agree that learners have a much higher and effective degree of knowledge retention when all their senses are actively engaged [9].

2.4 Technology based training/teaching (TBT)

Due to globalisation, economic pressures and work-life concerns, companies and academic institutions are looking toward technology for innovative and flexible training and education solutions [6, 10]. [10] Breaks TBT down into three levels namely basic, middle and high-end sophistication. On the basic level, technology such as CD-ROM, DVD, interactive video systems and e-learning are used for training. The next level includes electronic performance support systems and intelligent tutoring systems, which have the added capability of tailoring the training to the individual. At the high end of the continuum are technologies such as distributed interactive simulations, distributed mission training as well as game-based environments. Such highly sophisticated systems place learners or employees in simulated, realistic situations applicable to the job.

2.4.1 The shift to TBT

An initial and most common application of TBT is Information and Communications Technology (ICT). There has been a large degree of interest in ICT in recent years, as it is believed to improve educational efficiencies and to be useful in addressing educational shortcomings often found in developing countries such as South Africa [11]. The 2003 white paper on education, stipulated that by 2013 every South African learner in tertiary education should be ICT capable [12]. Furthermore an e-education policy was formulated in 2004 to equip all schools with ICT [11], in an attempt to improve the quality of education in South Africa.

Other than reducing costs and training times, TBT has the ability to surpass the standard classroom experience since it can be used to provide a personalised learning experience and monitoring of progress [10]. With so many advances in educational theory and clear advantages of TBT, it is at first not clear why the results are still so poor. It is thus important to identify why the education system in South Africa (as well as in many other countries) is underperforming.

3 WHAT IS WRONG WITH THE CURRENT SYSTEM?

In South African higher education institutions, 41% of students drop out, with between 50% and 60% of them dropping out in their first year. Of the 59% who remain, not all pass, as suggested by the university graduation rate of 15% [13]. The resulting questions raised are therefore: Why are so many of our students dropping out, and secondly; why are those who do not drop out, struggling to pass and not prepared for the practical work in industry?

3.1 Reasons for high dropout rates

A study done in America reported that 47% of respondents listed classes being boring as their main reason for dropping out, while 69% of respondents also admitted that they did not feel motivated to work harder [14]. When asked how the education system could be improved, the top two suggestions made, each with a convincing 81%, were that there should be more experiential learning and opportunities for real-world learning, and secondly, better teachers who actually make classes interesting. Very similar comments echoed in the classrooms of South African institutions such as Stellenbosch University.

3.2 Stuck in their old ways

The positive projections for ICT in South Africa in the 2003 white paper did not materialise. Despite the move toward a more student-centred, constructivist learning approach incorporating TBT (more specifically ICT), many educators have stuck to their traditional ways of teaching. In a study on ICT use in South Africa, educators were asked why they were not implementing TBT into their lessons [12]. 75% of respondents gave "[the] necessary computers were not available" as one of their reasons for not having implemented TBT. 36.8% noted that they did not have sufficient preparation time, while 25% admitted to not being confident enough with technology, and 17.9% said that integrating technology into lessons is simply too difficult. In the same study however, 93% of educators indicated that they did have access to computers, although mostly in a designated computer room. Interestingly, educators with more than 21 computers available per class were the least willing to integrate it into their teaching, raising questions about the validity of the excuse of computers not being available. Regardless of the reasons, experts are in agreement that instruction alone, is simply inadequate to prepare students for today's competitive environment [3, 9].

3.2.1 Instruction's inability to adequately prepare learners

The problem with an instruction-based approach to teaching is that it incorrectly assumes that knowledge can be directly transferred by means of facts [8]. The assessment methods implemented in such an approach are usually summative (i.e. writing a test or exam at the end of the module) and do not allow for feedback and rework to take place [4]. The student has one, sometimes two opportunities to demonstrate his/her knowledge and pass the module. This theoretical rote learning does not stimulate the student's problem solving ability, nor does it prepare learners for a world in which practical knowledge is a necessity [15]. Instead, it leads to students adopting the attitude of "Will this be in the exam? Otherwise I do not need to know it".

3.3 Getting TBT wrong

A study conducted in 2000 on the use of ICT in South African schools, concluded that it is not always that the technology is not available, but rather that the educators do not know how to use it [16]. A common misconception of TBT is that it is simply the use of some form of technology in a classroom environment [16]. Many educators use technology as add-ons and replace existing manual methods without actually providing any useful interaction [4, 5, 9, 16]. [16] Explains this problem in relation to the South African Teacher Development Framework provided by the Department of Education. In education, there are five teacher capacities as depicted in Figure 1. The lowest levels are the entry and adoption levels, in which educators are only capable of limited use of ICT due to lack of resources or more often, technological skills. These stages relate to the basic level of TBT sophistication discussed in Section 2.4. The adaption and appropriation levels include educators who are able to adapt technology and apply it in manners in which the student's education is enriched, and thus relate to the middle level of TBT use. The highest and desired level is that of innovation, in which an educator is able to develop an entirely new environment in which the flexible use of ICT allows for interactive and collaborative learning. This in turn relates to the high end sophistication level of TBT use.

Figure 1 – The teacher development framework

Due to reasons ranging from lack of technical experience to unwillingness to change, South African education is struggling with the successful adoption of ICT [12]. Replacing blackboard notes with PowerPoints and written tests with online tests, the majority of educators are stuck in the lower levels of the framework. Where technology is being used for such purposes, it is redundant and of no benefit to the learner [16].

3.3.1 Learner perceptions of ICT

Although seldom applied effectively, the appeal of ICT to students is clear. In a South African schools study conducted, 94% of learners reported that they felt more motivated, and 83% that they obtained a more in-depth understanding when learning with ICT [12]. Other benefits of ICT use included that it:

- accommodates different skills levels (85%);
- gives more, more relevant and faster feedback (92%);
- allows for collaboration (88%); and
- provides for more creative thinking (88%).

3.4 Information overload

Regardless of whether or not technology is being used instead of manual methods, education in South Africa remains too didactic [17]. Excessive amounts of information, combined with the lack of constructive feedback, leads to a shallow understanding of the work, and encourages only surface learning [4]. Students become bored and whilst many drop out, others graduate having made no attempt to understand the work material, and enter the workplace hopelessly ill-prepared.

The question that can be raised becomes: how can we teach people in a way that will motivate and engage them, whilst equiping them with the problem solving and innovative skills they require in a real working environment?

4 A POSSIBLE SOLUTION

Other than reducing costs and training times, TBT exceeds the standard classroom experience since it can provide a personalised learning experience, monitoring of progress, increased engagement and facilitate more active PBL [4, 8, 10, 18], if applied effectively. These advantages, along with the increasing availability of technology provide for a strong support that it should be used to improve education.

In order for TBT to be effective, it should engage and motivate students, encourage self-learning and provide opportunities for collaboration and social interaction [4]. The feasibility and potential impact of TBT is clear, but how to implement it practically or innovatively, is less so.

4.1 Learning factories as an innovative approach for competence development

As a result of the growing interest in practical and experiential teaching or learning environments, as well as the use of technology in teaching [10], leading universities and colleges have reacted by establishing learning factories [22, 23, 24]. These physical, operational factories usually cover the whole creation process of a product selected in accordance with didactical criteria and serve as exemplary and realistic hands-on learning environments. The concept of learning factories integrates self-directed and action-oriented learning in heterogeneous groups to encourage implied experiential knowledge, integrated into a formal didactical concept. This enables the trainer to address the intended competences systematically by guiding the learners through the processes necessary to acquire the intended knowledge and professional and/or vocational competencies. This symbiotic combination of teaching professional expertise, methodical and individual competencies as well as some soft skills can be achieved by combing traditional, instructor-based teaching methods with hands-on sessions held in teamwork to improve social and group work competencies [25, 26]. The tasks or problems students get confronted with are inspired by issues of high practical relevance and designed openly to avoid predefined solutions or approaches. By using mostly commercially available technologies in learning factories, a very authentic learning environment can be created, resulting in a highly immersive experience for the learners [27]. Additionally, higher learning success is achieved by including the own actions of and the interactions between the learners into the learning experience compared to conventional teaching and learning methods [28, 29].

4.1.1 Qualification procedure in learning factories

To achieve the given objective of providing the learner with the relevant skills and competences a multi-staged qualification concept is used (Figure 2). This concept contains phases of self-study, instruction, practice and the self-dependent action and experience oriented application of methods within a comprehensive and complex task in the learning factory. The self-directed reactivation of basic knowledge helps to ensure that all participants have the same entry-level of knowledge, which improves time-efficiency of the actual training. To transfer new knowledge and methods, different teaching methods such as instructive and constructive learning are combined. This qualification part already takes place in the actual learning factory to familiarise participants with the digital and physical infrastructure used. The role of the trainer is becoming more and more passive, shifting from a pure instructor to a moderator or coach. Instead of providing learners with direct instructions as in the traditional teaching, a coach provides guidance but allows students to create and learn from their own experiences. Ultimately, the learners are confronted with a final qualification scenario. An example of such a scenario is where they receive all required information such as product and order data. Based on this information, the learners plan and design their individual operational, collaborative production system. The trainers are only assisting the learners in case of questions regarding the used technical assistance systems at this stage of the qualification procedure. During the actual operation of the factory the trainer may introduce turbulences, forcing the learners to reconfigure the work system.

An objective evaluation of the execution of the given task can be conducted based on specific indicators such as the capacity utilization, throughput times, quality performance indicators, on-time delivery or other relevant measures depending on the learning goals. Even more important than these objective criteria is the final reflection of the learner group regarding the methods learnt, decisions made and the exchange of individual experiences in accordance with the adopted role within the team.

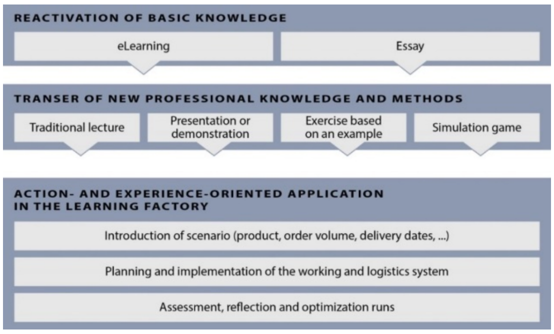

Figure 2 - Qualification procedure [30]

4.2 Potential to surpass the current learning factory experience

A learning factory provides students with a more interesting, real world, experiential learning environment than purely instructive teaching. It also involves students actively and allows for a high level of social interaction. It therefore satisfies the first three principles for successful learning that were discussed in Section 2.2. The final principle is that the environment must provide adequate feedback and allow for the reworking and improvement of ideas. Although the qualification procedure does provide for reflection, this only occurs at the final stage along with the assessment. The problem identified with assessment methods in traditional teaching was that they are summative, and do not allow for the reworking of ideas [4]. The learning factory therefore teaches students valuable lessons, but does not provide iterative opportunities to learn from experience, rework ideas and relearn.

4.2.1 Gamification

Whilst high end technologies as discussed are far better than traditional training, they still do not allow for a lot of interaction and communication between trainees, nor do they allow for adequate feedback loops [10]. A new and improved branch of game-based training is gamification, which is largely dependent on the interaction and cooperation of trainees. Gamification takes aspects from games, and places them into the actual job environment, taking advantage of the high levels of engagement games have to offer, and implementing this into the workplace. [28] Looks at how gamification can offer a fun and engaging learning environment and provide the user with constant feedback regarding their work, allowing for continuous rework. Another benefit of gamification is that it can be adapted to each learner's capabilities – the task at hand is always perfectly balanced so as to be challenging, yet never be above the player's current abilities, which provides high levels of motivation.

4.2.2 Feasibility of gamification and TBT

The generation born between the 1980s and the early 2000s, known as generation Y or the millennials, are the group of young adults who will be entering the higher education system as well as the workforce in the years to come. It is therefore important to assess the potential that game-based learning has for this generation. [19] Provide an interesting view on this, describing a generation they call the game generation. The game generation is the combination of generation X (born between the 1960s and 1980s) and generation Y. This is the group of people who grew up in a world where games have, so to say, defined their lives. Games and technology are everywhere and people from this game generation will have a very difficult time trying to picture a world without it. The use of TBT shows great promise for such a generation, where gaming is simply the norm. [19] Go further to suggest that growing up with games has shaped the game generation into being very capable employees and even top managers.

In South Africa specifically, the gaming industry holds a very bright future. Although poor broadband limits online gaming in South Africa, the mobile gaming industry is expected to contribute to 39% of South Africa's gaming industry by 2017, in comparison to a mere 8% on a global level [20]. A study in 2013 showed that despite the high poverty rate, over 75% of South Africans classified into the low income group and above the age of 15, own mobile phones [21]. Gamification thus shows great potential, leaving only the task of how it can be incorporated into a teaching/training environment.

4.2.3 A training need in South Africa

In South Africa, a topic that is continuously found in headlines, is the corporative attitudes between business employers and labour unions. There is no working together, but instead, the high levels of confrontation lead to frequent strikes and lost production which eventually result in large scale retrenchment due to financial strains. The Workplace Challenge (WPC) is a South African government initiative to support the introduction of employee participation programs in South Africa [32]. Its aim is to incorporate employees in the business, and develop good relationships between business and labour unions. Team-based work organisation (TBWO) was introduced into 12 sections of 5 small and medium sized manufacturing firms. TBWO, more commonly known as shop floor management, addresses lean principles as well as soft skills within a business, as portrayed in Figure 3.

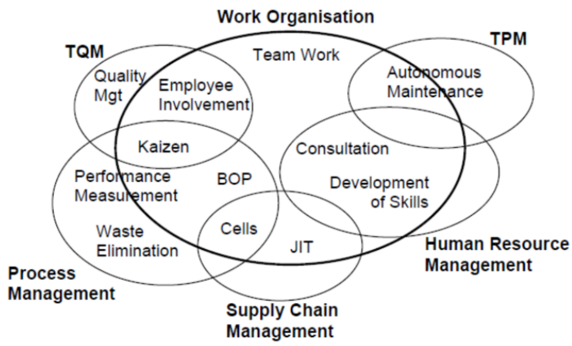

Figure 3 - Practices associated with TBWO [32]

Teamwork and decentralised decision making has been adopted in many companies and has shown to improve overall efficiencies as well as employee motivation. The WPC was conducted over a very short time span of 2 years, and whilst not all participating firms had clear cut results, the potential impact of shop floor management in South Africa is undeniable [32].

4.2.4 CIRP Conference

The topic of learning factories in South Africa was addressed in the 2015 CIRP conference held in Cape Town in August 2015. A large group of researchers, industry experts, government representatives, as well as academics were present from around the world. In a workshop led by Prof. Dr.-Ing. Hummel, attendants were asked which concepts they believe should be demonstrated in a learning factory. Whilst concepts such as manufacturing and logistics were also listed, an overwhelming number of attendants reported that they would like to see more of the softer skills addressed in such an environment, as it is crucial for the business world but difficult to teach otherwise. Another theme which was very prominent in the feedback was that of lean basics. A learning factory generally consists of a model production line in which physical, mechanical and logistics systems are evident. Lean basics such as 5S and Kaizen are generally incorporated directly into the production line, but students never fully grasp the impact of not employing such concepts. Soft skills such as project management, communication, multicultural interaction, and leadership, are less prominent. Although the learning factory does involve teamwork and project management, the inadequate feedback does not allow students to fully realise the impact of e.g. bad attitudes and miscommunication on the company. These skills are not as easy to conceptualise and teach, since they cannot be taught by instruction and human behaviour is almost impossible to model accurately.

4.3 Gamification's potential in learning factories

In such a case where instruction is inadequate, one should look to more innovative solutions such as gamification. Games could be used to accurately simulate real world interactions in the work place, the impact of clean workstations and reduced waste, the effect of human error and poor communication, as well as inter-racial and –linguistic conflicts. They would also provide a more motivating and stimulating learning environment, for topics which many students may find boring and obvious, yet lack the definite skills in. Learning factories already provide the practical skills, but adding this dimension of games and simulations provides the opportunity to teach shop floor management (including lean basics and the softer skills) that form a crucial part of any business today, in a fun and innovative way that keeps students motivated and engaged.

5 CONCLUSIONS

Stellenbosch University is currently in the initial planning phase of developing a learning factory in the Department of Industrial Engineering. The potential for gamification is clear, but whether or not it has a lasting effect remains to be seen although the trends suggest so.

To assess the effect of gamification within the learning factory, a learning module will be developed for the addition of gamification into the Stellenbosch learning factory. The still conceptual plan is to design a gamified module for "Shop floor management" to teach lean basics as well as soft skills. The game will be designed and implemented into the module by means of scientific or experimental validation. In such a validation procedure, one has a control group and a test group. In this case, the control group will be a group of students who partake in the module in the basic learning factory without gamification. The test group will partake in the gamified version of the module, still within the learning factory. The two groups will then be assessed to determine whether the addition of gamification had any impact on their understanding and results.

The full potential of a more constructivist teaching approach can only be reached if both teaching and assessment methods are redesigned. It is the aim of this project to assess the potential of gamification in the learning factory, and contribute to the redesign of the learning environment at Stellenbosch University.

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Integrating Resource Efficiency in Learning Factories for Industrial Engineering.

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Abstract
The electrification of tomorrow's mobility concepts requires a lightweight design of automotive chassis. In order to save energy during the use phase of those cars, established material like steel are part wise substituted by composite materials. Looking at the manufacturing processes for composites, new technological challenges arise considering all aspects of sustainability. Hence, an industrial engineering learning factory was developed to increase sustainability during the manufacturing of composites products. The learning scenarios in this factory cover human factors engineering, energy efficient operations and economic improvements. Towards the implementation of a green factory a didactic learning concept was developed in order to train future industrial engineers during their studies as well as engineering people on-the-job. This paper contains the presentation of the developed learning scenarios and quantifies the practical impacts of the taught methodologies while applying them in industrial use-cases.

Keywords
Sustainability, Resource Efficiency, Learning Factory, Carbon Fibre Reinforced Plastics, Composite Materials

1 INTRODUCTION

Due to the ongoing climate change and the limited availability of fossil fuels, industries across Europe are forced to increase the sustainability of their operations in general and their energy efficiency in particular [1-3]. Since the disposability of energy is a critical factor for economic success, energy efficiency is being addressed broadly as an upcoming political goal [4, 5]. Therefore our research work elaborates and accesses methodologies to increase the sustainability performance in discrete manufacturing. Besides social and economic issues, the ecological perspective is challenging to address, especially in Germany, where the completion of the nuclear phase-out is envisioned for 2020.

Action is needed to close the perspective gap in power generation capacities. Hence a joint strategy was formed combining efforts to increase the usage of renewable energies and the implementation of energy efficiency measures. Whereby efficiency measures are expected to contribute with a share of 30 percent, decreasing total electrical energy demand. During a series of case studies, being conducted by the authors, the feasibility of efficiency increases in manufacturing operations was demonstrated [6-8]. To enhance the broad distribution of those findings to industrial applications, learning factories serve as suitable platforms to discuss, demonstrate and disseminate methodologies and technological solutions among industry decision makers and engineering students [9].

Hence this paper presents the results and the methodologies involved in a structured reengineering process for machine tools and production plants. Besides methodologies involving life cycle thinking are presented and evaluated in the context of lightweight design. Finally didactical concepts are presented on who to embed both concepts into the environments of learning factory on resource efficiency.

2 PROCESS OPTIMISATION WITH REGARD TO RESOURCE EFFICIENCY

2.1 Introduction to resource efficiency

The importance for sustainable management of industrial companies is increasing. Often talked about under the term "Corporate Social Responsibility", respective management methods have been implemented by many companies [10].

Sustainability is a concept, which is often discussed on an abstract level. It is generally addressed from three perspectives covering economic, environmental and social aspects. A more concrete approach on industrial practices is conducted within the concept of resource efficiency, which stimulates the efficient use of natural resources and within these, especially the consumption of material and energy. In practice, energy efficiency is tackled often, while material efficiency is neglected frequently. However, a look at recent statistics from the German federal statistics agency shows that material costs can take up a substantial part of total costs of industrial companies: In producing companies in Germany, 43.4 % of the total costs are material costs, energy costs only 2.1% (while personnel is 17.9 %) [11]. This of course gives only a limited view, but since Germany still has a considerable manufacturing industry, it shows the importance of the topic in general.

Increasing resource efficiency has also been set as a national German and a European goal (as specified in the German resource efficiency program “ProgRess” and the European future strategy “Europe 2020” [12, 13]. Another international resource efficiency initiative has recently been started by the G7 countries during their 2015 meeting in Germany [14].

Many companies have started to implement technical and organizational measures to increase resource efficiency. Examples of good practice from Germany can be found on the website of the “VDI-Zentrum für Ressourceneffizienz” [15]. The site also supports the identification of potentials for operational resource efficiency by means of quick-check questionnaires. Furthermore, examples on international resource efficiency tactics are presented in the results of the project “Resource Efficiency Atlas” [16, 17]. Besides a schema developed by Roberts and Ball supports practitioners while searching for practical examples on how to implement sustainable manufacturing practices including aspects of resource efficiency [18]. Recently the German engineering association VDI has published the guideline VDI 4800, which shows how to address resource efficiency in practice. The final draft has been discussed publicly and the final version is due for publication in the upcoming months [19].

But which concrete measures can be carried out to increase resource efficiency inside of a company? The following points are frequently mentioned [20]:

- Optimisation of production processes (e.g. to reduce cutting losses)
- Increasing the capacity utilisation of machinery and plant equipment)
- Reduce the amount of rejects
- Recycling of materials and components
- Improved product design or better engineering design (where helpful by using lightweight design principles)
- Optimisations involving other companies as well (especially customers and suppliers)

In the following paragraph, methodologies to assess energy and material efficiency are presented. This is followed by an introduction into aspects of life cycle thinking and the concept of material input per service unit (MIPS); a concept that support the usability and application of life cycle assessment of products and technologies.

2.2 Assessing material and energy efficiency in manufacturing

2.2.1 Methods

Resource efficiency can be influenced significantly during the product’s design phase. Yet, assessments also need to be conducted in existing machinery in order to gain information on how to improve both present and future product generations for resource efficiency. The following section proposes an approach on how to conduct an assessment in a structured and methodological way. Besides, the findings of its application are presented giving the example of a large-scale production plant with a length of more than 300 feet and an electric drive power of approximately 1 MW. Using flexible measurement systems and computer aided technologies (CAx), energy and life cycle performance can be translated into indicators (KPIs) [21]. The hereby obtained transparency is helping to combine resource efficiency and monetary aspects, hence supporting competitive manufacturing.

2.2.2 Case study: Resource efficient reengineering of large scale plant as a role model to be included in learning factories

The plant illustrated in fig. 1 is analysed according its resource efficiency potentials. This plant is operated 24/7 in a three-shift system.

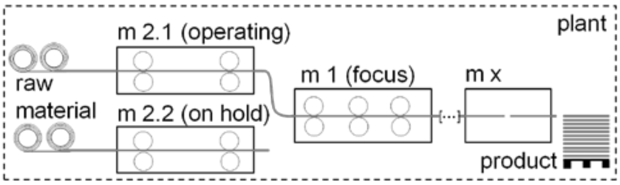

Figure 1 - Simplified functional scheme of the analysed plant consisting of several (n) machines (acronym: m) [6]

Different product variants result in an alternating power consumption of the production plant. This is especially true for the most energy consuming parts, the drives.

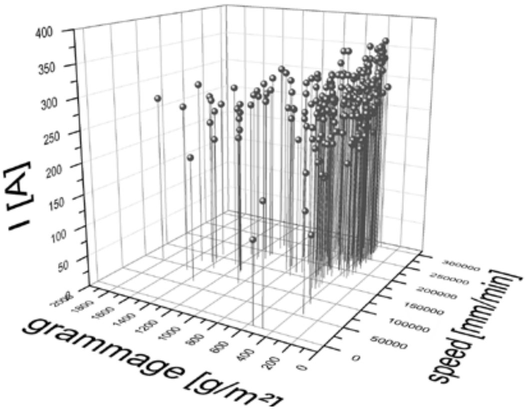

Figure 2 - Correlation of the plants operating parameter and its energy consumption during a period of 96h manufacturing [6]

Therefore, the production schedule during a manufacturing period of 96h was analysed. As an intermediate result, the product variances described by grammage of the raw material and the plant speed were correlated (fig. 2). To derive possible reengineering measures, the electric DC- main drive system consisting of gearboxes with a nominal power of 260 kW was examined in detail.

As a finding of the power measuring, the histogram illustrated in fig. 3 clearly reveals an over-dimensioning of this drive by more than 30 percent: the maximum power recommended was 179 kW and the average power consumed was 111 kW.

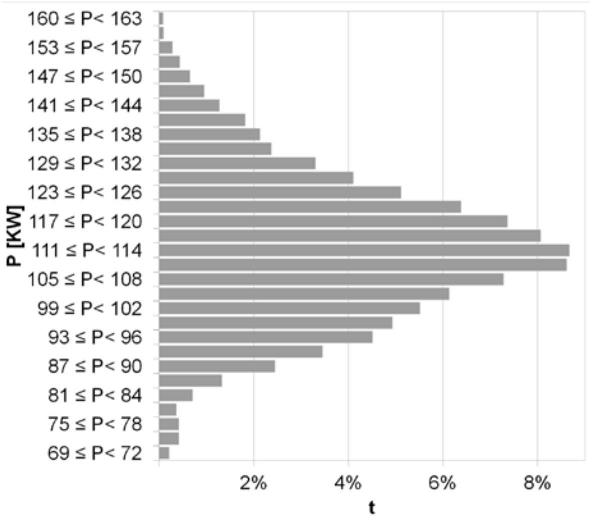

Figure 3 - Histogram showing the aggregated measuring data of the analysed electric main drive of the plant at initial state [6]

As a reengineering measure the drive system was re-dimensioned by using two direct driven AC-torque motors, thus improving the average motor efficiency of initially 80 percent. The optimised operating point led to an increase of motor efficiency by 12 percent, resulting in annual energy cost saving of 14,000 € during the plant's utilization phase of more than 20 years (fig. 4).

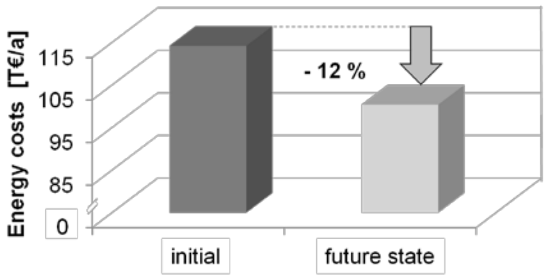

Figure 4 - Assessment of the obtained energy savings during the plant's utilization phase

Looking at the elaborated synergetic benefits on material efficiency the costs were reduced due to the following measures: smaller motors, elimination of gearboxes, weight reduction of accelerated masses and in the electric cabinet. As shown in fig. 5 the material costs thereby where cut by one third.

Looking at the implications of this case study on competitive manufacturing, the significance of considering all parties involved in the plants life cycle is shown. First, the manufacturer who profits from increased margins as a result of reengineering efforts.

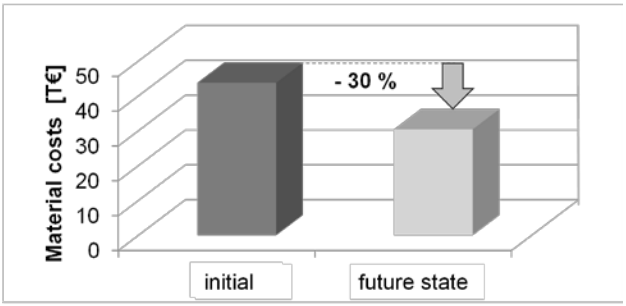

Figure 5 - Assessment of the obtained material savings during the plant's design phase

Second, the customer and operating company profit from the reduced annually energy costs during the plant's utilization phase.

As an outlook for future more distinguished methodologies need to be considered. Therefore the next section gives a brief overview on suited approaches:

2.3 Assessing material and efficiency over the life cycle

2.3.1 Methods

Life cycle thinking is the basis for a holistic assessment of products, services and production technologies and it can be used to identify concrete actions on how to reduce material and energy consumption. Therefore it considers all life cycle phases from "cradle-to-grave" including the extraction of raw materials, the manufacturing of intermediary and final products, the energy consumption during the use and end-of-life phase (e.g. disposal and/or recycling) [22].

Methods that apply life cycle thinking are referred to as Life Cycle Assessment (LCA) or Carbon Footprint and are described for example by Klöpffer, Grahl, Hottenroth and Schmidt [23, 24]. They are based on data for material and energy flows occurring during the different phases of the life cycle. Data is measured in practice or can be obtained from databases such as EcoInvent 3, Gabi, ELCD 3.0 or others. The result is a life cycle inventory that lists all material as well as energy inputs and outputs. Experts use software tools such as SimaPro 7, Gabi6, Umberto NXT LCA or OpenLCA or simply a Microsoft Excel spreadsheet in combination with a LCA database [25]. In the life cycle impact assessment, quantitative environmental impact is determined, (e.g. contribution to global warming effect, to stratospheric ozone depletion or to toxicity). However, understanding the relevance of such a result is often difficult for non-LCA practitioners. In a practical setting, that is often a main obstacle for carrying out a detailed life cycle assessment (another one being limited availability of data). Thus, simplified methods, such as the material input per service unit (MIPS) as described by Schmidt-Bleek can be helpful [26].

Life cycle thinking can help to clarify whether or to what extent a product, service or technology relies on critical raw materials. This question has come into focus for many companies in recent years due to an increasing demand for materials such as platinum, indium or rare earth materials like neodymium [27, 28]. A life cycle perspective can clarify which materials are used, how they are produced and where the required raw materials are mined. Thus related risks can then be assessed, e. g. by using the concept of criticality [29].

Hence, life cycle thinking creates an information bases, which can be used to assess environmental impacts and potential risks coming from the use of critical materials. Moreover, the transparency gained from life cycle thinking helps identifying optimisation potentials for reducing material and energy consumption.

2.3.2 Example

The MIPS method determines the material intensity per service unit by considering only input flows of materials, energy and processes used over the life cycle of a product, service or technology. As a simplified life cycle thinking method, it does not directly regard emissions. The mass of materials used over the whole life cycle is expressed as the material intensity and is specified in kg/kg. It considers the weight of all natural resources used. Energy consumption is incorporated by using data describing the material input of energy production.

For instance, producing 1 kg of gold requires 540 kg of abiotic material and 1 kg of Aluminium 18.98 kg of abiotic material, 539.21 kg of water and 5.91 kg of air [30].

A good example on how to use the described methodology in an industrial application was shown by Hufenbach and co-workers in the research project MaRess [31, 32]. It is therefore described in the following paragraph.

In automobiles such as the Volkswagen Golf, a seat shell is generally manufactured out of steel including a steel pipe and four steel sheets and weights 4.6 kg. A novel way for manufacturing such a shell implies the use of glass fibre reinforced polypropylene. As a result of using this lightweight structure the weight of the product could be reduced to 2.3 kg.

The MIPS analysis for both product alternatives considered different materials, production technologies and fuel consumption during the vehicles use phase. Material and energy flows were determined and relevant data obtained and aggregated. The required resources were distinguished in the categories “abiotic material”, “water” and “air” and expressed in kg. The obtained results are displayed in fig. 6. The data shows that the overall resource consumption can be reduced by using the lightweight structure. Furthermore (not shown in the figure), the production of the raw material for the steel alternative uses more abiotic material and more water (but less air).

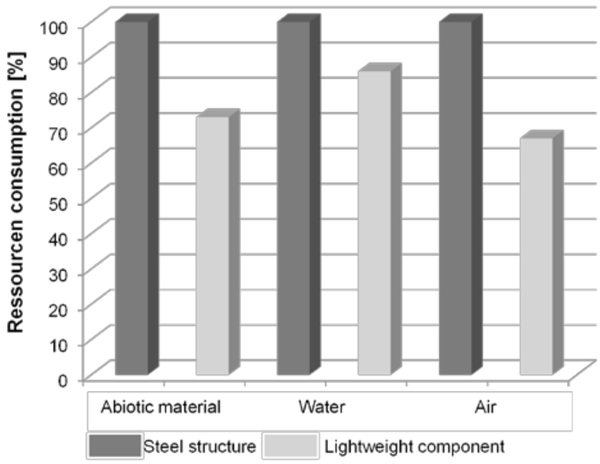

Figure 6 - Results from the MIPS analysis comparing steel and lightweight structure of a VW Golf back seat shell. [32]

However, the component manufacturing of the lightweight structure uses more resources (in all three categories). The lower weight reduces the fuel consumption of the automobile. This leads to a reduced resource consumption during the use phase and for the overall resource consumption over all life cycle phases.

To conclude, the analysis lead to a positive result for the lightweight structure. The underlying model can be used to evaluate different scenarios in order to improve the technology during its development and planning of production systems or while comparing production process alternatives.

3 EMBEDDING RESOURCE EFFICIENCY AND LIFE CYCLE THINKING IN LEARNING FACTORIES

The methodologies presented in section 2 have proven to support the efforts to increase resource efficiency in industrial engineering. Though the importance of considering life cycle aspects in learning factories has already been acknowledged, it is still far from having achieved widespread dissemination [33]. Therefore the challenge arising is how to transfer the related tools effectively into practice in order to constantly extend its circle of users.

Learning factories have shown to be useful environments to teach students or industry practitioners how to assess resource efficiency and how to optimise processes in a factory [34, 35].

At Fraunhofer Bayreuth, a learning factory called Green Factory Bavaria is currently been set up. Its goal is to support the German “Energiewende”, by offering a comprehensive learning facility so as to enable and incentivise industry decision makers and students to improve resource efficiency in their particular sphere of influence.

3.1 Learning methods

From the context of learning methods and transfer concepts, the learning objectives when teaching university students or industry practitioners vary considerably.

Considering prior knowledge of participants four different learning goals can be identified:

- Learn how to apply methods to assess resource efficiency over the life-cycle of a product, technology or service. (Analytical methodology)
- Learn how to analyse production processes with respect to cost aspects, material and energy consumption (Holistic and neutral view)
- Learn how to analyse a complex technical and organisational production set up (Process know how)
- Learn how to apply such knowledge in their respective area of application (Best practice implementation)

Considering the individual learning goals of the addressed target groups university students and industry practitioners differ. Considering their initial experience supports specifying their training demand. Therefore table 1, illustrates a comparison derived during interviews with participants before seminars.

Learning goals	University students	Industry practitioners
Holistic and neutral view	◐	●
Analytical methodology	○	◐
Process know how	◐	○
Best practice implementation	●	◐
Legend: Initial training demand:● high ◐ medium ○low		

Table 1 - Comparison of initial training demand for specific learning factory target groups

On the one hand it is obvious that students have a profound knowledge of methodologies, while their experience to implement best practice solutions is still lacking. On the other hand practitioners need to refresh their capabilities in analytical methodologies and to sharpen their holistic view. Here a training in mixed audiences can support know-how transfer in between those groups complementing one another.

Hence a modular didactical approach was created in order to meet the mentioned individual learning goals for university students and industry practitioners.

3.2 Development of life cycle based scenarios for a learning factory

As described in 2.3.2, lightweight design is an important engineering strategy for future mobility concepts in order to reduce resource consumption during a vehicles use phase [36]. Besides the related manufacturing process implies the use of a wide range of production equipment with multiple opportunities to analyse and identify potential to reduce energy and material consumption. Consequently the technical process chosen for the learning factory is a manufacturing process for products made from composite materials e.g. carbon fibre reinforced plastics (CFRP). The respective process chain comprise both thermal energy intense processes like curing or cleaning and consumers with dynamic loads like a milling centre used for mould production or a cutter used for the confectioning of composite plies (ref. fig. 7).

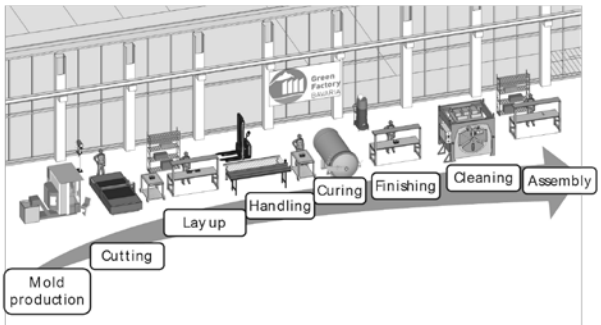

Figure 7 - Process chain of the Green Factory Bavaria

In the first training module participants are asked to apply a life cycle based assessment of different production scenarios using the MIPS method presented in 2.3.2. For that purpose they are provided with data on energy and material consumption for all steps of the process chain.

Given different production scenarios for a defined sample product with defined lot sizes, participants are asked to evaluate strategies to reduce resource consumption in the different process steps targeting lowest all over resource consumption.

For instance in the step “mould production” the energy consumption during machining of different mould materials e.g. steel, aluminium, polyurethane (PUR) is presented. Due to different speed and feed rates energy consumption varies in the range of 10 to 15 percent, favouring soft materials. Yet, participants are asked to reflect on interdependencies and resource consumption in subsequent process steps. Thus preventing a one-sided view on resource efficiency in single process steps.

Considering the process step “curing” the selection of polyurethane as mould material favours the use of one-sided moulds in an autoclave or oven process, with vacuum bagging. Yet other curing technologies such as a heat press or resin transfer moulding (RTM) are difficult to use since mould integrated heating is not possible and a preheating stations would be required. Besides the decision for PUR based moulds effects clean-, reuse- and recyclability of production resources, since tool life is considerably lower compared to steel or aluminium moulds, therefore implying earlier replacements or rework of moulds.

Considering all life cycle phases, participants are also educated on problems related to the design and end-of-life of products that use composite parts or multi-material-structures. Thus stressing the importance of material choice during product design and the importance to consider of repair, remanufacture and recycling processes during product- and process development.

3.3 Evaluating reengineering efforts in the scope of a learning factory

Another learning module educates on how to conduct resource efficient reengineering projects as discussed in section 2.2. Trainees need to understand industrial processes and their resource consumption. Therefore participants are educated in the design and set up of flexible measurement and visualisation concepts. For instance during the analysis of the process step “cutting” trainees receive the measurement data on actual power demand of a previously setup measurement system on a mobile energy monitoring device, thus following the idea of cyber physical systems. During teamwork practices they learn how to interpret those measurement data by applying Energy Performance Indicators (EnPIs) and how to derive suitable optimisation measures. In this case the interpretation leads to a reengineering of the vacuum pump due to a significant over-dimensioning of about 40 %.

The last mentioned more dynamic and complex characteristics of the electric drives are rather challenging to access. Therefore different game-based learning methods have been developed in order to identify components and optimisation potentials in an interactive manner [9]. Applying the methods described in 2.2.2 training participants find that in the current state these machines are all characterized by over-dimensioned drives.

In order to realise the identified saving potentials the drive system has to be substituted. Having two machines available in different drive configurations (initial drive setup vs. modified drive set up) is not economically feasible for a learning factory environment. Thus the verification of savings is demonstrated by suitable test rigs. Those rigs serve as miniaturised machines to demonstrate energy and material savings.

Furthermore the accessibility of large-scale plants for training is limited. Hence test rigs also represent a suitable alternative for the visualisation of best practice solutions. For that purpose the Green Factory includes a simplified test rig as shown in fig. 9, consisting of different electric drives which can be compared on aspects of energy efficiency.

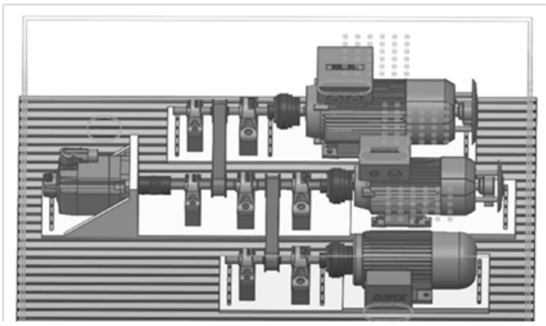

Figure 8 - Simplified test rig consisting of alternative electric drives

4 OUTLOOK AND CONCLUSIONS

The application of life cycle methods in the learning factory requires the collection of additional data on resource consumption due to the usage of prime material and production resources but also on energy consumption in the individual steps of the manufacturing process.

Considering further improvements of test-rigs and machine show cases the reuse of waste heat from the step “curing” for ambient heating or preheating of bathes in a cleaning machines is being investigated. An integration into the Green Factory Bavaria is planned for the end of 2016.

In extension to the established industrial engineering and lean management approaches, the integration of resource efficiency and life cycle thinking significantly prospers competitive manufacturing. As a result of the conducted work, a critical success factor for both education at universities and training for professionals is the design of learning factories. This paper discussed an approach how to simplify and to fit complex engineering methodologies in the environment of learning factories. The next step is the integration of the developed didactic elements in a new lab building (vision: fig. 9).

Figure 9 - Outlook: Integrated learning environment at Green Factory Bayreuth

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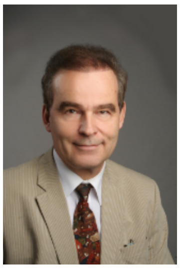

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Preparing Production Systems for the Internet of Things The Potential of Socio-Technical Approaches in Dealing with Complexity

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Abstract
The Internet of Things will influence how production systems of the future will work. An expected change is the increase in complexity when production system will start communicating with each other. This complexity can be managed by applying socio-technical approaches. This includes analyzing a production system regarding the domains: tasks, actors, technology, and structure. We identified three topics per domain that we think need further investigation, as they may influence complexity to a strong degree. For tasks we suggest looking into urgency, habituation, and strategies; for actors we suggest looking into skills, human factors, and user diversity. In the field of technology we find visualization, decision support, and interactions to be most pressing, while in the field of structure we see responsibility, delegation, and communication.

Keywords
Socio-Technical Systems, Human Factors, Complexity, Digitalization, Cyber-physical Systems

1 INTRODUCTION

The address space of the protocol IPV6 allows addressing 3.4×10^{38} unique identities [1]. This allows giving every device on the planet a unique identifier and alongside the possibility to communicate with its peers. This will also allow production systems to communicate their state, their task, and their capabilities. Production systems in the future will we be intricately connected, allowing never before seen individualized and automatized production [2]. Machines will be able to adapt the production process automatically to highly individual products in accordance with their capabilities, capacity utilization, and cost-effectiveness. These cyber-physical systems or the Internet of Things [3] will influence working environments heavily, but will also spur new innovation [4].

Increasing the individualization of products causes on-the-fly restructuring in shop floor logistics [5,6] and increases the repertoire of skills needed by workers at each individual workplace to handle individual operations for each product. Increasing the level of automation increases the dependency of manufacturing machinery from the manufacturing set-up on the shop floor as a whole and its communicative capabilities. Both changes increase the amount of complexity of the shop floor in general. This increase of complexity within a factory is matched by an increase of the complexity in supply chain logistics. In order to fully leverage digitalization of production systems, all operators, planners, engineers & managers must be enabled to handle the complexity inherent in these systems [7].

But not all complexity is created equal [8]. Complexity is often misused as the sheer difficulty or size of a problem, but essentially it refers to the intricateness of problems alongside its difficulty and size. Some forms of complexity are easily solved by computers (e.g. large divisible problems) while others are more easily solved by humans (e.g. object recognition). Most relevant complexity will require both humans and computers to address problems collaboratively. To make things worse, this collaboration produces further complexity to be managed.

So what is necessary to cope with the increasing pervasiveness of digitalization in production systems? Certainly investing in improving the skill-set of workers and engineers is necessary to enable them in dealing with the challenges of complexity. But complexity takes different forms (e.g. perceptive, cognitive, task-related, etc.) and modes (e.g. incidental, continuous, expertise resistant, etc.), and therefore different tolls on different users [8]. Designing socio-technical systems with the diversity of users in mind and context adaptive to both user and task has the potential to lift the burden of complexity off the user. Still little is known what human factors determine how well different forms of complexity are managed. We propose a research outline to investigate the influence of human factors on complexity in production systems in order to develop methods, tools and social practices to deal with new forms of complexity in socio-technical systems.

2 SOCIO-TECHNICAL SYSTEMS

A socio-technical system is an organized system of humans and technology that is structured in certain fashion to solve specific tasks. A typical approach to model such a system was proposed by Leavitt [9], which visualizes the interrelation of the subsystems (see Figure 1).

The technical sub-system on the one hand contains the *task* and the *technology* to solve the task, while the social sub-system contains the *actors* and the *structure* and *roles* that govern the interaction. Both sub-systems are said to benefit from each other. The interactions between the systems are said to determine the success of the whole system. Designed features of the system are said to have linear cause-effect relationships in the interaction and can be planned. The more interesting features are the unplanned, non-linear emergent relationships in such systems, which may be good or bad.

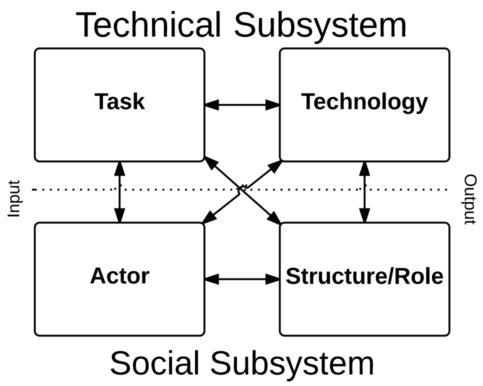

Figure 1 - Adapted Socio-Technical System, cf. [9]

These unplanned relationships are also often the cause of complexity in the system. Trying to manage these relationships (e.g. through organizational rules) can introduce new complexity into an organization, as the amount of additional features (e.g. circumvention strategies) may again increase non-linearly with the amount of managerial effort put into place.

3 COMPLEXITY

Complexity can occur in multiple locations in a production and manufacturing process. In order to understand where complexity matters, we must first understand who will have to deal with the complexity – who, what, where and how. Future production system will incorporate further meshing of human and machine operators in order to fulfill the increasing demand of individualization and mass-customization. The integration of information and communication technology in production processes, will bring new challenges regarding security, usability and trust in interoperability of the systems [10].

3.1 The human operator

Even with drastically improving machine-learning capabilities humans – and for a while so – are champions in the domain of dealing with novel problems. If the question that needs answering is neither clear nor known, human operators are required to deal with a problem. Future production systems though will have a complexity hardly comprehensible with the skill-set of single human operator.

But not only the skill-set of a human operator is unique. Human factors (e.g. perceptual and motor limitations) and diversity (e.g. cognitive capabilities or personality structures) plays a large role in human individuality and influences performance in dealing with tasks in cyber-physical systems [7,11].

Given the demographic changes in most industrialized nations, talents and skillful workers will be a scarce and diverse resource [12]. Thus management of skill-sets and capabilities and the management of the knowledge thereof can become crucial in effectively operating a production system. Mapping available workers to processes in shifts should be managed and planned ahead. Doing this with classical managerial approaches though, might also lead to an increase in complexity in the organization.

3.2 The technology-interface

The ever-increasing complexity that is hidden behind the interface of a technological artifact is unknown to most users. Still most interfaces are complex in their design and do not support the user in completing their tasks. Particularly in professional settings cognitive ergonomics are ignored and “efficient” solutions are produced. But saving time on developing solutions that do not cater to the users’ needs is time saved at the wrong place. In the long run more time – and not just time – will be saved, when enough attention is given to optimizing a user-interface for a given task.

The question remains though: What is an optimal user interface? Given the complexity of user diversity, a singular answer will hardly suffice. Giving users the option to customize their interface just begs the question. A serious approach should incorporate human factors and user diversity using adaptive interfaces. But adaptive to what?

3.3 The cost of complexity

Basic interactions with interfaces and their associated costs are quite well understood. Fitt’s law for example measures the cost of a pointing interaction as consumption of time from the parameters distance and target size. The influence of user diversity (e.g. age [13]) has also been incorporated into the equation. But even simple interactions of interface, user, and task complexity have only recently been investigated [11]. But what is the cost of delegation of a complex task to a younger user with less experience, under time pressure with high responsibility? Models to understand the interaction of users und technology, when embedded in a given structure for a given task are needed in order to improve the understanding of production systems and to design technology that optimizes complexity costs for any given scenario.

How to achieve this, is still unclear. We propose a research outline to tackle some of the questions, which we deem to be important first steps.

4 RESEARCH OUTLINE

In order to address the above-mentioned challenges we suggest the following research outline.

The core idea of the research outline is to use methods of human-computer interaction (HCI) and iterative user-centered development to optimize the technical systems and task-analysis and job design to improve the social subsystem.

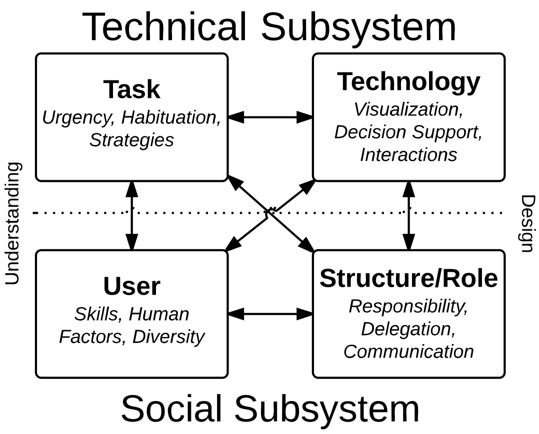

Figure 2 - Four domains of Socio-Technical Systems and suggested research areas

The four domains (i.e. task, technology, worker and structure) are addressed simultaneously and related to each other. We would like to address the following sub-aspects in the four domains individually (see Figure 2).

4.1 Task Domain

Task complexity has been approached in multiple fashions. Its complexity is often imputed from criteria such as time pressure, habituation, multi-variate decision making, task clarity, goal-conflicts, redundancy, and many more [14]. In a production system that needs to quickly adapt to new production procedures we assume that the following criteria are most pressing.

Urgency is the extent to which a task needs quick completion. Not just in planning the task earlier in a schedule but also in completing the task in shorter time frames.

Habituation is the consequence of the reoccurrence of a task. If the task needs to be repeated exactly the same over and over again, habituation may free cognitive resources and improve motivation [15]. If the task often changes habituation may never occur. The uncanny valley is the area where habituation occurs and slight changes in the task are overlooked because of habituation.

Strategies are the mental procedures that workers associate with a task to either put a system to good use or circumvent cumbersome actions to fulfill a simple task. A typical circumvention strategy for the task “sharing a document between co-workers“ is to avoid the haphazardly designed CSCW solution and use a commercial service such as Dropbox, thus enervating the organizations data security by exposing data to a third party [16].

4.2 Technology domain

HCI approaches can be used to understand the interrelation of users and technology and furthermore its usability. A technology that is used in an organization shapes the understanding of tasks, skills, and communication processes in an organization, intricately influencing the success of an organization. Under the changes of the Internet of Things and Big Data we assume the following aspects of technological artifacts will need further investigation.

Visualization of information can be used to instantly access large amounts of data, but only so if the data is properly mapped to the perceptual dimensions. Features such as dimension reduction, entropy detection, and hypothesis generation are important because relevant questions may still be unknown but important for the organizations success.

Decision support can be implemented in monitoring system to aide the operator in finding optimal machine configurations. Here questions of transparency, comprehensibility and trust are of high importance to allow the user trace the decision suggestions, evaluate consequences, and make an informed decision.

Interactions of a system should be designed to facilitate the users skills in solving the task at hand. The famous pinch-to-zoom gesture on a multitouch-tablet, drastically improved the accessibility of an interaction pattern of “locate x on a spatial map”. Nevertheless, an expert mouse user might be faster using a scroll-wheel and a high-dpi mouse. The interactions should adapt to the users needs in regard of the context, bearing in mind the role of the user in the larger context.

4.3 User Domain

Different users cope differently with complexity in different usage contexts. Mapping a task – and thus its complexity – to a user that is both capable and motivated enables an organization to handle fluctuating staff even under individualized production settings. Failing to facilitate user diversity will hamper innovative capability and thus organizational success. Aspects that need to be addressed are the following:

Skills of the users may vary. Some skills may be correlated others may be independent. Often skills are not actively managed or part of organizational knowledge. Human resource management could include skill and competence features, which would allow mapping workers to tasks in context-optimal settings. Often the expert is not available, but an advanced worker may be able to complete a task with a support system. Additionally managing staff fluctuation from a skill-based perspective helps prevent loss of talent [17].

Human factors or *ergonomics* address the limitations and variance in human perception and ability (e.g. spatial perception and cognition), when interacting with a system. Incorporating human limitations is necessary, but optimizing user-task fit can improve work satisfaction and yield.

Similarly *user diversity* addresses the variance in human diversity. For example, users can have different motivations for work, different personality profiles and different values. All of them play a role in matching a user to a task. Giving a user a task that contradicts his values and motivation will yield worse outcomes, than matching them up.

4.4 Structure domain

The structure of an organization (and the roles attached to it) can heavily influence the complexity of the organization. Structure inherently reflects the organizational culture by implying procedures of work. The more levels of hierarchy exist in an organization the more formal procedures will be. Production systems might require changes quickly, even when some consequences are oblique to the person in charge. Having fewer levels of hierarchy may lead to faster decision making in urgency scenarios. We think the following aspects of structure need further investigation.

Responsibility in future production system must be handled differently. A user that makes a decision using a decision support system or a visualization may not be solely responsible for the outcome (be it either good or bad). When algorithms do pre-processing on different levels who is responsible for errors of human-machine interaction? Furthermore how will this possible shift in responsibility affect the users motivation and zest?

Delegation means the outsourcing of tasks to subordinates or colleagues. In high-skilled teams the best suitable worker may not be determined, as all might be suitable, having different benefits. Giving a task to a less qualified worker as a planned procedure can be seen as a means of learning-by-doing, when task-settings can be adjusted to suit the novice. Analyzing the context, finding goal measures, and choosing a goal-setting that improves short- and long-term organizational goals, may be crucial to efficient work delegation.

Communication lies at the heart of all organizational efforts, for without communication no organization is present. Understanding how communication affects intra-organizational development, when changing aspects of an organization (e.g. technology or structure) is crucial for a successful organization. Planned and purposeful communication is particularly important when approaching a change from a socio-technical point of view. Unplanned ad-hoc communication shapes the real structure of an organization [18] and must be understood, if an organization is to succeed.

4.5 Bringing the domains together

All domains have been traditionally address by HCI, ICT, and IS research. Bringing all domains together is the benefit of socio-technical approaches. For example, questions can be asked that address the change of an organization when switching to hybrid-assembly technology. Using both robots and humans in assembly processes has effects on all four domains. As robots now conduct some of the tasks the set of tasks fulfilled by workers will change. This in turn will change the skillset of workers. Acceptance of the robots will also depend on a variety of worker diversity criteria (e.g. trust in technology). Lastly, changes in structure will occur (e.g. creation of a robot programming department) to cater to the change in organizational needs caused by the use of robotics. Designing models to predict or test these changes is necessary. Applying constant change is adequate [19, 20].

5 SUMMARY

The Internet of Things and Industry 4.0 bring along changes for production systems that will increase complexity for workers, organizations and technology. Applying socio-technical approaches to these scenarios are promising as they address both technical and social sub-systems. Therefore, we proposed a research outline to address different aspects of socio-technical-systems that we consider most pressing for each domain.

Understanding both *task* and *user* and designing *technology* and *structure* to optimize organizational success is the goal of applying a socio-technical approach.

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8 BIOGRAPHY

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The Global Evolution of the Industrial Internet of Things – A Cross Country Comparison Based on an International Study on Industrie 4.0 for Asset Efficiency Management

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Abstract
Digitalization is changing the industrial landscape in a way we did not anticipate. The manufacturing industries worldwide are working to develop strategies and concepts for what is labelled with different terms such as the Industrial Internet of Things in the USA or Industrie 4.0 in Germany. All concepts have in common to take advantage from the communication in the internet of things and the extensive analytics of all available information. Embedded and cyber-physical systems play a dominant role to realize new processes. A paradigm shift in manufacturing management logics towards real time, autonomous and self-controlled systems is envisaged. The overarching objective is to produce and deliver highly customized products and solutions at every place in the world at highest efficiency and for the cost of mass manufacturing. On a global scale, the speed of implementing the concept and successfully gaining first experiences seems to be crucial for industrial nations to take industrial leadership. The objective of this paper is to provide results from a global survey on the state of implementation and the future perspectives of the concept Industrie 4.0. Study results are presented within the context of a conceptual reference framework developed by the German government and industry leaders. The study was conducted in 2015. We took a focus on asset efficiency management. The study polled 433 industrial manufacturing executives in five regions – China, France, German speaking countries, the United Kingdom and the United States. We developed a specific capability maturity model for our analyses. The results provide an understanding of industry preparedness for Industrie 4.0. The huge potential of Industrie 4.0 is clearly pointed out but there are significant differences between countries. This paper reports the status today and the aspiration for 2020 by asset efficiency levers, industry and production type, and country.

Keywords
Industrie 4.0; digitalization; Industrial Internet of Things; asset efficiency management; business transformation; capability maturity model

1 INTRODUCTION

The fourth industrial revolution succeeds great industrial innovations including the steam engine, the conveyor belt as well as the first phase of information technology [1]. Industrie 4.0 is enabled by cyber-physical systems where electronics, intelligent sensors, computation, and networking are embedded into physical systems and processes [2]. This combination of the cyber and the physical builds a complex, closed-loop system. Machines can operate in tandem with each other and their users in real-time. Factory processes become visible and controllable in a virtual space. With real-time decision-making, products can communicate to machines on how to process [3]. Supply chains flexibly align themselves based on changes in demand or production capacity.

This uber-efficient scenario far exceeds today's traditional processes in every way possible, and we believe this is a great opportunity for innovative companies and research institutes to dynamically shape the future. Effective management of production systems in any industrial facility is one of the most important contributors to its profitability. Enterprises that implement the best-in-class strategies to manage their physical assets stand to succeed in the global marketplace. And with the technology strides that have taken place over the past five years, there are significant opportunities for enterprises to improve the efficiency of their assets and in turn increase their productivity and profitability [4]. With this in mind, Infosys, a global leader in consulting, technology, engineering, outsourcing and next generation services, conducted the first global study on asset efficiency along with the Institute for Industrial Management (FIR) at RWTH Aachen, the largest and leading scientific, technical and research university in Germany. The objective of the study was to find out how well today's industrial organizations are taking advantage of technologies to leverage value from their assets. The study observes how organizations plan to undertake this technology journey in the years leading up to 2020.

This paper also provides an interesting comparison among types of industries and nations by looking at the leading organizations in five advanced manufacturing countries. It provides insights that industrial enterprises around the world can use to help develop their roadmap for improving asset efficiency.

2 OBJECTIVE AND METHODOLOGY

This comprehensive global research study assessed industry attitudes towards Industrie 4.0 and specifically asset efficiency in the aerospace, automotive, electronics, machinery and process industries in China, France, German speaking countries, the United Kingdom, and the United States. The study polled 433 executives through an online survey as well as telephone interviews. FIR at RWTH Aachen and independent research firm Vanson Bourne conducted the study for leading information systems provider Infosys; FIR at RWTH Aachen surveyed German respondents between January and March, 2015 and Vanson Bourne surveyed the remaining countries between February and March 2015. To qualify for the survey, respondents had to be relevant executives involved in plant or production management (especially manufacturing managers, plant technical managers, COOs, and asset efficiency consultants as well as early adopters of R&D and manufacturing).

For the purpose of analysis, enterprises were categorized as “Early Adopters” or “Followers” based on their response to the levers of asset efficiency. This paper reports the status today and the aspiration for 2020 by asset efficiency levers, industry and production type, and country.

The study focused on the four most important asset efficiency levers namely, maintenance management, operational management, information management and energy management. Respondents were asked to outline their current maturity levels on these levers and their target for 2020 on a four point scale of ‘Not Implemented (lowest maturity)’, ‘Potential Recognized’, ‘Partially Implemented’ and ‘Systematically Implemented and Benefits Realized (highest maturity)’. The research used the Industrie 4.0 framework, conceptualized by the German government and developed by industry leaders, to investigate the effectiveness of existing asset management processes [5]. This reference framework is therefore applicable to any industrial organization in the world.

3 JOURNEY TO INDUSTRIE 4.0 EXCELLENCE

Leaders of high-tech industrial enterprises understand that their most important assets are the machinery and assembly tools on their factory floors. These companies have often spent decades developing their manufacturing plants to produce an ever increasing array of goods and products that they sell around the world. They have also spent decades improving their industrial processes – including just-in-time inventory – to be as efficient as possible. But given the technology developments that have taken place over the past five years, even the industrial enterprises that are the leaders in lean processes are in danger of being left behind in the 21st century. This is because merely the deep knowledge of industrial practices is not enough to succeed in today’s ultra-competitive and technology-enabled marketplace. Industrie 4.0 has not only impact on the efficiency of enterprises but also on business growth (see Figure 1).

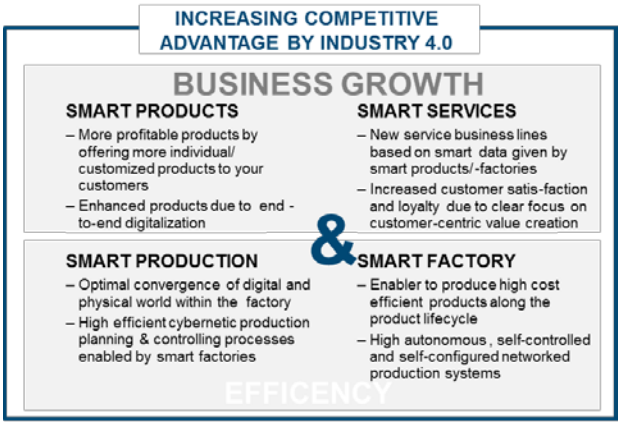

Figure 1 - Impact of Industrie 4.0 on business Growth

Industrie 4.0 in our perspective is the combination and seamless collaboration of different interdependent elements:

- Data capturing for single assets.
- Monitoring of the capturing data.
- (automated) analysis of the data on local level.
- (automated) analysis of the data on enterprise level.
- Closed loop: automated optimization loops to the assets based on the analyzed data.

By tapping into the principles of Industrie 4.0 and adopting emerging technologies, todays asset-intensive organizations can hone their ability to stay ahead in a new world where machinery and tools are being amplified by digitization. This cyber-physical world offers the bold riches of enhanced global competitiveness and entry into radically new marketplaces.

Lever	Scope	Impact
Maintenance Efficiency	Using real time operational and conditional data for planning and scheduling maintenance and to implement preventive maintenance	An effective and relevant maintenance strategy can help in controlling maintenance cost, which is the single largest expenditure in an asset-intensive enterprise
Operational Efficiency	Integrated real-time visibility to monitor all levels from the individual asset to the entire supply chain	An integrated view on asset performance efficiency, production efficiency and logistics process efficiency automatically managed by closed control loops results in massive increase in overall equipment efficiency
Information Efficiency	The handling of available data. It provides high data quality and therefore interoperability for a seamless flow of data	Good asset information management significantly improves decision-making ability, especially in determining optimal asset performance and maintenance
Energy Efficiency	Optimizing the consumption of resources (energy, raw materials, water, chemicals and waste) of the plant	There is a direct relation between asset efficiency and energy efficiency. An efficient asset is also energy efficient

Figure 2 - Impact of Industrie 4.0 on efficiency

4 RESULTS

4.1 Benchmarking global Industrie 4.0 maturity

The study shows that awareness has not been reflected in action, yet.

While the vast majority (85 percent) of companies are aware of the high potential in implementing Industrie 4.0 concepts to increase asset efficiency (this is consistent across countries and sectors), only 15 percent of enterprises surveyed have already implemented dedicated strategies for asset efficiency. An additional 39 percent have partially implemented these strategies.

Nearly half of the respondents surveyed (48 percent) want to implement Industrie 4.0 solutions systematically for enhanced asset efficiency by 2020 (see Figure 3). Conversely, by 2020 still one fifth of the respondents will have made at best piecemeal progress.

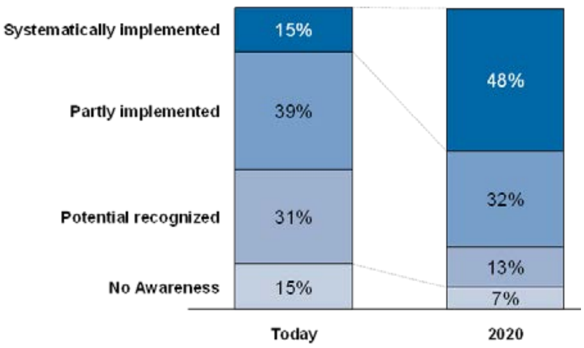

Figure 3 - Use of Industry 4.0 concepts to manage assets

The survey found significant variance in the adoption levels in different markets. Figure 2, below, shows that in 2015 68 percent of respondents from China have partially or systematically implemented asset management programs, rising to 89 percent by 2015. Comparable numbers for France are 27 percent and 58 percent respectively.

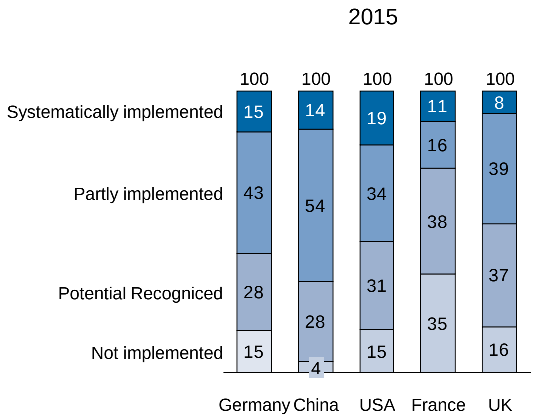

Figure 4 - Country comparison of Industrie 4.0 concepts to manage assets in 2015

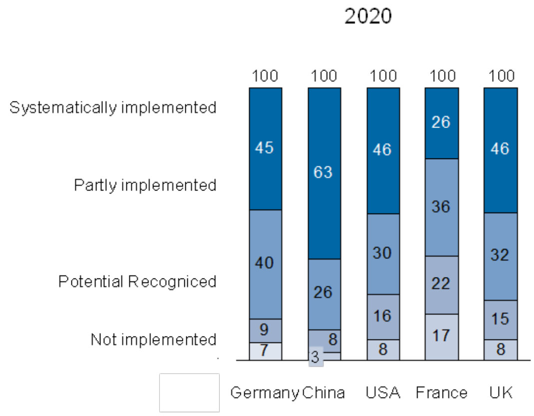

Figure 5 - Country comparison of Industrie 4.0 concepts to manage assets in 2020

4.2 Industrie 4.0 international comparisons

Across the five countries surveyed - China, France, Germany, the United Kingdom and the United States – the level of maturity in Industrie 4.0 varied significantly. While no country can claim to be the global early adopter in implementing Industrie 4.0 in the context of asset efficiency, the percentage of companies in China that claim to be early adopters is significantly higher than anywhere else (see Figure 6).

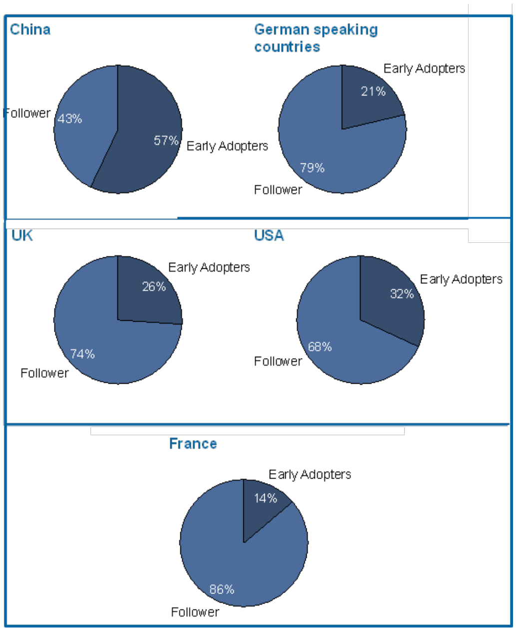

Figure 6 - Early Adopter and Follower analysis by country

It is expected that a number of factors are driving this; notably the focused initiatives and investment from the Chinese Government to develop more sustainable industry growth. Also manufacturing is core for China and the market is accustomed to rapidly implementing new technology, especially in green field sites free of legacy infrastructures.Germany (21 percent), the United Kingdom (36 percent) and the United States (32 percent) have similar maturity footprints both in terms of 2015 status and 2020 ambition. This could be because of their historical leadership in manufacturing. In France (14 percent), the Industrie 4.0 implementation is comparatively less mature. The economic downturn and recent unsuccessful digitization programs could be contributing factors.

A comparison of the average maturity rate in 2015 and the expected rate in 2020 reflects this progress of Industrie 4.0 adoption. The study also reveals that the rate of progress expected in each country over the next five years is expected to be the broadly the same. However, in France average maturity rates are expected to be lower in 2020 than Chinese companies are, on average, claiming in 2015 (see Figure 7).

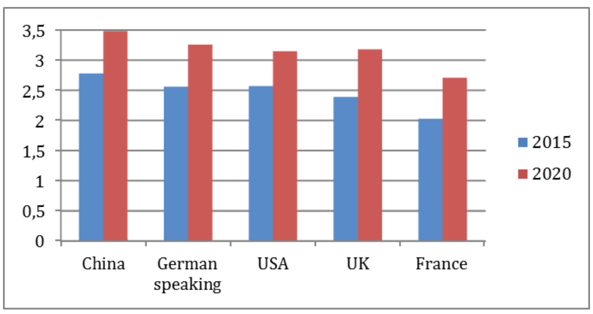

Figure 7 - Asset efficiency maturity level by country

4.3 Industrie 4.0 sector comparisons

The study was conducted across a variety of sectors including aerospace, automotive, electronics, machinery and process industry. Currently the automotive, electronics and process industries have the highest maturity levels and the machinery, aerospace and process industries have planned the most extensive improvements between now and 2020 (see Figure 8).

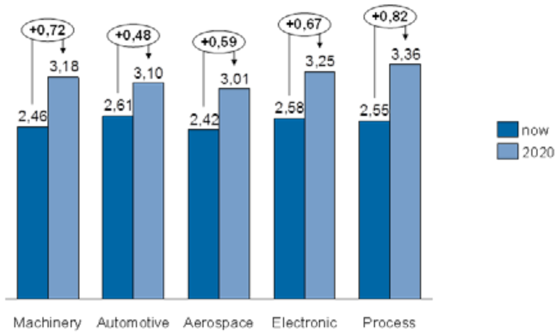

Figure 8 - Comparison by industry sector

However, these differences are not as pronounced as the country comparisons. While automotive and process industries currently have the highest maturity levels, this may be of little surprise as they are sectors which have benefited from significant investment in technology. The process industry, for example, has a long history in the application of sensors in processes to control and regulate complex process chains.

The study also reveals that the largest improvements will take place in the following fields:

Data Standards & Interoperability: this is a precursor for seamless interaction between different machines and -systems, and also enables further aspects of efficiency up the value chain.

Root-Cause Analysis: RCA is an important aspect as it solves the problems at their source, rather than just fixing the apparent. This is therefore considered as a key for any improvement process, and rightly so, as it focusses on a holistic approach rather than localized decisions [x].

Dynamic Asset Classification: A clear understanding of the assets based on their relationship, hierarchy an criticality is an important aspect to build the right productivity model that improves Operational and Maintenance Efficiency.

Production planning & scheduling: This covers all aspects of operations, from workforce activities to product delivery and is primarily concerned with the efficient use of resources. This therefore focusses on real-time balancing of different variables to achieve an optimal performance. The integration, interoperability and collaboration of different systems therefore become critical.

Knowledge Management: Knowledge capture and management is becoming increasingly important in the asset intensive industries due to the ageing workforce. This is an essential enabler of an efficient maintenance process; people and their knowledge play an important role for maintenance and repair activities on more and more complex machines; knowledge of all employees therefore needs to be collected and provided in an efficient way.

Figure 9 - Planned effort in the next 5 years

5 CONCLUSIONS

The next five years will be vital to the adoption of Industrie 4.0 for many global industries. Infosys has identified six leadership characteristics that will help ensure a strong foundation for success:

1. Information management needs to be improved for maintenance and operational efficiency. Industry wide data standards need to be agreed and implemented; data security must be a constant focus.

2. Fundamental skill shortages exist in a number of key areas – principally open source and data technologies, although there will be others over time. Being nimble and flexible in how these skills are resourced will be critical.

3. Implementation needs to be faster than most companies are prepared for. Hence a robust ecosystem and open partnering behavior will be necessary.

4. Those with legacy infrastructures can succeed, but they may need to adopt innovation more aggressively. This can be achieved not only through the bold use of technology, but also in building new partnerships with companies, large and small, research organizations and academic institutions.

5. Focusing on quick wins and building on these can bring advantage. For example energy efficiency is monitored, but not yet managed. Managing energy efficiency could be a simple first step to get traction.

6. This is a revolution in manufacturing that can be predicted. Embracing the inevitable change and building a clear roadmap that can flex over time are critical. In order to stay a step ahead, companies must constantly look to learn from competitors and other companies outside their traditional sphere.

Digital technology, no matter how new the assets on the factory floor are, can further transform machinery and a company's processes to enable them to be ultra-efficient. As we head towards 2020, the measure of performance in the manufacturing industry is becoming dependent on the efficiency of a company's production systems. And performance will be the difference between industry leaders and followers.

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7 BIOGRAPHY

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Strategic Guidance towards Industry 4.0 – a Three-stage Process Model

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Abstract

Manufacturing processes have changed significantly since the early days of the steam engine and Henry Ford's assembly line. After Ford's mechanization and the first digitalization of industrial productions in the 1970s, currently a fourth industrial revolution (commonly referred to as Industry 4.0) is taking place. Industry 4.0 propagates a vision where recent developments in information technology are expected to enable entirely new forms of cooperative engineering and manufacturing. A key idea is that intelligent products and machines – driven by real-time data, embedded software and the internet – are organized as autonomous agents within a pervasive and agile network of value creation. While realizing the potential of these new concepts today's manufacturers experience substantial problems in bringing ideas down to the shop floor. Problems occur mainly due to different perceptions about the principal nature of Industry 4.0, the broadness and complexity of related topics, the expected impact on the strategic and operational level and – as an inevitable consequence – the concrete measures needed to transform towards an Industry 4.0 ready company. In this paper we suggest a three-stage process model to systematically guide companies in their Industry 4.0 vision and strategy-finding process. The proposed model has been applied and advanced within various real-world projects. Results show a strong need for guided support in developing a company-specific Industry 4.0 vision and roadmap.

Keywords

Industry 4.0, Industrie 4.0, Internet of Things, Industrial Internet, Smart Manufacturing, Technology Roadmapping, Co-Innovation

1 INTRODUCTION

Europe's industry is facing substantial economic challenges due to an increasing pace of societal and technological developments, such as decreasing availability of natural resources, natural disasters and warfare, increasing energy prices, increasing age of employees and globalization of markets. Moreover, consumers increasingly demand for improved product-service innovation, product variety, quality standards, support services, and immediacy or order satisfaction.

These challenges need industrial enterprises that are capable of managing their whole value-chain in an agile and responsive manner. To be more specific: companies need both - virtual and physical structures that allow for close cooperation and rapid adaption along the whole lifecycle from innovation to production and distribution [1].

Recent governmental and industrial initiatives sketch a future scenario where recent advances in computer and manufacturing technology are exploited to enable a new way of business operations and especially manufacturing, commonly referred to by the term Industry 4.0 – the fourth industrial revolution (see Figure 1).

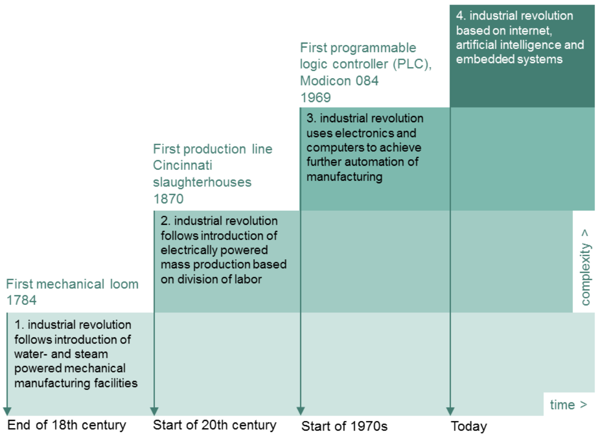

Figure 1 - Four industrial Revolutions (see DFKI 2011)

Accordingly, the internet and supporting technologies (e.g. embedded systems) serve as a backbone to integrate physical objects, human actors, intelligent machines, production lines and processes across organizational boundaries to form an intelligent, networked and agile value chain.

New approaches to business and manufacturing operations are realized through four main focus areas [2]:

- Vertical integration of all layers of a production system
- Horizontal integration of all partners in a value chain
- Lifecycle-engineering across the entire value chain
- Acceleration through exponential technologies

It is obvious that such a futuristic – yet realistic – scenario imposes substantial challenges to today's companies.

On a practical level, especially for small and medium enterprises, challenges arise mainly due to the immense financial resources required for the acquisition of new technology. For example, Germany's companies in various branches are expected to invest 650 million Euros into Industry 4.0-related technologies and applications in 2015 [3].

On a strategic level, experiences from several strategic orientation workshops with various companies have shown that companies face a twofold challenge with regard to the concept of a fourth industrial revolution. On the one hand companies have substantial problems to grasp the idea of Industry 4.0 and relate it to their specific domain. For example, they may not decide whether it is to be understood as a vision or it is rather a mission (ends versus means). On the other hand, they struggle to identify strategic fields of action, programmes and projects to move towards an enterprise in the sense of Industry 4.0. The latter problem is a consequence of the first problem area described – the lack of understanding for the concrete relevance and benefit of Industry 4.0. However, experiences show a general need for guidance in finding a proper strategy towards coping with the challenges imposed by Industry 4.0.

In this paper we suggest a three-stage process model to systematically guide companies in their Industry 4.0 vision and strategy finding process. In section 2 we discuss the concept of Industry 4.0 and summarize the main challenges for European manufacturing companies regarding their transformation towards Industry 4.0. In section 3 we suggest a three-stage process model to systematically guide companies in their Industry 4.0 vision and strategy-finding process. Finally, in section 4 we summarize first experiences from the field.

2 THE CHALLENGE OF INDUSTRY 4.0

Several surveys aimed for shedding light on the rather slow realization of Industry 4.0. A study carried out by IBM in 2015 shows that high investments and costs, the complexity and required know-how, as well as the unsuitability of existing IT-Infrastructure and technologies are the main restraints for realizing Industry 4.0 [4].

Investments are mainly needed for the implementation of modern information and communication technology as well as up-to-date machinery, which should result in a digital transformation of the company's entire business operations. Currently fragmented IT-systems, outdated machine parks and a high degree of manual work disable horizontal and vertical integration along the value chain. These issues are enhanced by the incredibly tiny margins, under which conservative industry operates that prevent investments into uncertain areas such as Industry 4.0. This uncertainty about Industry 4.0 is triggered by the high complexity of the topic and a lack of existing road-maps and guidance towards the realization of the visions and concepts [5] - [6].

2.1 Vision or Mission

The vision of Industry 4.0 propagates a fundamental paradigm shift in production industries, which is characterised by a new level of socio-technical interaction. Small, decentralized networks are acting autonomous and are capable of controlling themselves in response to different situations. These, so called smart factories are embedded in the inter-company value network, which is encompassed by end-to-end engineering, resulting in seamless convergence of the digital and physical world.

The results are smart products that are uniquely identifiable and locatable at all times during the manufacturing process. Smart products are customizable and the incorporation of individual customer- and product specific features into the design and configuration is enabled - at the costs of mass products.

On an employee level, the Industry 4.0 vision propagates, that workers are able to control, regulate and configure smart manufacturing resource networks and manufacturing steps. Routine tasks are taken over by machines, so that employees can focus on creative, value-adding activities [2].

Overall, the vision of Industry 4.0 describes a whole new approach to business operations, and especially the production industries. The sophisticated and complex vision of Industry 4.0 is based on the missionary approach of strengthening Europe's and especially Germany's conventional manufacturing industry - as described in the high-tech strategy the German government has initialized. Advanced manufacturing systems should support Germany's position in competition with the re-industrialization taking place in Asia and the US.

So far, companies seem to struggle when transforming the visionary ideas of Industry 4.0 to a missionary level of increasing the productivity on the shop floor. One reason could be found in the isolated implementation of parts of the Industry 4.0-vision (e.g. implementation of 3D-printing).

Practically, only the collaborative implementation of all the concepts of Industry 4.0 has to be followed to increase the so called collaborative productivity in production industries [7].

2.2 Technology or Methodology

The four main characteristics of Industry 4.0 state "*acceleration through exponential technologies*" as the enabler for horizontal and vertical integration along the entire value chain. However, companies tend to focus too much on the technological aspect in Industry 4.0 in order to attain short-term market advantages.

As Industry 4.0 is based on the concept of cyber-physical systems (CPS), which is mainly a technological approach, aspects such as the modification of organizational structures and processes, the adaption of existing business models, or the development of necessary employee-skills and qualifications are neglected.

The National Academy of Science and Engineering in Germany states that Industry 4.0 is "…best understood as new level of organization and control over the entire value chain of the lifecycle of products…" [2], which describes Industry 4.0 as a paradigm shift in business operations, rather than a technology-based improvement of production capabilities.

The reasons why many companies consider Industry 4.0 a mainly technological improvement are mainly facilitated by the either too complex or too vague descriptions of the new paradigms of Industry 4.0. In contrast, the implementation of aspects such as cyber-physical systems and modern information and communication technology allows for clearer measures to be taken on an operational level.

2.3 Revolution or Evolution

In retrospective, industrial revolutions always lead to a significant increase in productivity which increased the standard of living, and, therefore influenced the society fundamentally. The first three industrial revolutions have been stated as such ex post – triggered by the industry on the shop-floor [8]. In contrast, the 4th industrial revolution is postulated ex ante – triggered and promoted by the government and several related initiatives.

Also the level, where Industry 4.0 comes to action, shifts from the shop-floor to the overall engineering-processes and organizational brainwork within companies. Therefore, the industrial change initiated by Industry 4.0 is addressed highly diverse in literature [9], and no common ground is offered to companies.

Collaboration at all levels and the integration of processes builds the base for increasing collaborative productivity. Therefore, extracting distinct factors such as the implementation of modern technology and holding them responsible for triggering the 4th industrial revolution can result in a narrowed approach to Industry 4.0.

Moreover, during past industrial revolutions, companies reacted to an increased demand from the market which leads to the introduction of mechanical- and mass production. In contrast, the fourth industrial revolution requires companies to act self-reliant, without a clear demand for increased productivity from the market-side [7]. As a result, it is likely that distinct approaches of Industry 4.0 are going to be implemented at faster pace than others (depending on the actual pressure from the market), which indicates a more evolutionary character. However, the implementation of Industry 4.0's concepts in collaborative manners might trigger revolutionary changes in production industries.

3 A PROCESS MODEL FOR TRANSFORMING INTO AN INDUSTRY 4.0 READY COMPANY

To address the above outlined challenges we propose a process model as a guiding framework for Industry 4.0 vision and strategy building. The main goal of the model is to guide companies in developing their specific Industry 4.0 objectives along with a set of measures to reach them. Systematically carrying out the stages will take a company to their company-specific vision and roadmap, enabling a company to clearly communicate respective objectives and take concrete courses of action (see Figure 2). To develop the model we mainly built upon the concepts of co-innovation [10]–[12] and strategic road mapping [13]–[15]. In the following each stage is described in detail.

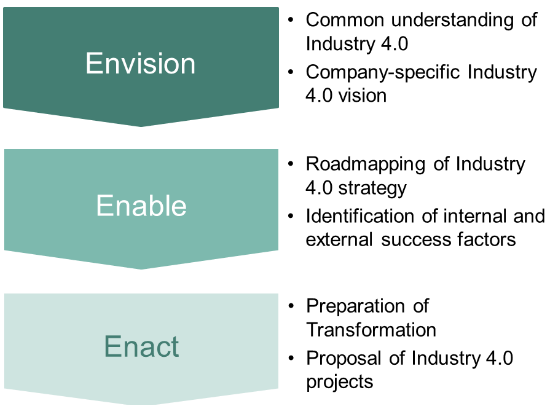

Figure 2 -Three-stage model for Industry 4.0 transformation

3.1 Stage 1: Envision

Within the "Envision" stage a company acquaints itself with the general concepts of the Industry 4.0 vision, develops its own understanding and aligns general Industry 4.0 ideas with company specific objectives and customer needs. The goal of this stage is to arrive at a company tailored Industry 4.0 vision that takes into account peculiarities of the industry and company environment. Stakeholders from top management are primarily involved, but also important business partners and customers are invited to take part in this phase. Broad commitment to the outcomes is reached through a participative approach where members of middle management are actively involved in vision development. At this stage, also external experts are involved to present relevant best-practices and to give important impulses towards vision building.

The stage of vision development is divided into an input oriented phase and an output oriented phase. Within the input phase the conceptual pillars of Industry 4.0 are explained through selected external experts. This leads to a shared understanding from a largely theoretic point of view. Experts' input is followed by a presentation of best-practices and promising examples from the company's domain of action, preferably by practitioners. The latter serves as a way for benchmarking and to raise awareness for the need for immediate action.

Finally, the company's current state of vision is presented through internal stakeholders. Having the big picture of Industry 4.0 and the company's state of vision at hand stakeholders are subsequently advised to develop their company specific Industry 4.0 vision in a collaborative way. The output oriented phase is dedicated to merge visionary concepts and ideas towards a consistent and concrete picture for the company of the future. Within this phase important questions such as the suitability of current business models, the appropriateness of the organizational skillset and the fitness of the current technological infrastructure are questioned and evaluated.

A company running through the stage of "Envision" is encouraged to do this in a collaborative way. In the spirit of co-innovation this means that the company has to extend its focus from the corporation to the whole value network including relevant business partners, suppliers and customers into the vision development [16]. The output of this stage is a company tailored vision for a future end state that withstands future challenges proclaimed by the new industrial revolution. The vision in terms of strategic road mapping answers the question where a company wants to go in the long-term future. The vision of a company should therefore be stated in a semantically unambiguous way, but generic enough not to presume the means (the strategies) for reaching the desired outcome.

The Industry 4.0 vision of a company is not meant to be a carefully programmed business model but should reflect a courageous picture of the company's future that takes into account the company's actual strengths and at the same time expected market, technological and societal developments. E.g. a car manufacturer that develops a vision towards completely transforming into a utility providing company where the product car is completely transformed into a public utility or a standardized service offering like "transportation". Such a vision statement may as well refer to concrete characteristics of a future product or service offering like self-driving car" or a future manufacturing system that autonomously schedules production orders and orders required materials based on actual and future customer demand.

3.2 Stage 2: Enable

The "Enable" stage is dedicated to break down the long-term Industry 4.0 vision into a more concrete business model and to develop principal strategies towards its successful implementation [17], [18]. Strategies answer the question of what has to be done to achieve the desired outcome.

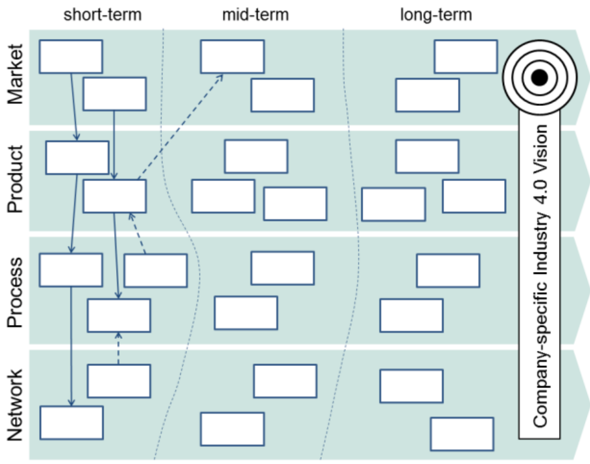

Figure 3 - Exemplary Industry 4.0 Roadmap

To facilitate the strategy planning and alignment process we use roadmapping as a technique for visualization and structuring of strategies (see Figure 3). Roadmapping allows sketching strategies and external constraints on separate layers against a common timeline. For our purpose we use a distinction into four strategic perspectives: market, product, process, and value network. These perspectives are represented by four layers. These layers constitute the vertical dimension of the roadmap whereas the horizontal dimension reflects the timeline.

Each layer is basically used to sketch the expected development of a related perspective:

- the customer segments (the market perspective),
- the value proposition (the product perspective),
- the key resources, technology and activities (the process perspective)
- and the necessary partners (the network perspective) needed to fulfill the value proposition.

The mapping of dimensions is performed in a top down fashion, starting from the market perspective where prospective customer segments are identified thus indicating the principal development of future demand characteristics, e.g. that a customer segment is expected to emerge that no longer owns cars but buys a transport service from A to B instead. From this future market developments product features, products or product lines are derived. The products identified lead to the processes needed to develop and manufacture them.

The process perspective therefore relates strongly to questions of which manufacturing and information technology is required for a future competitive production system. With regard to Industry 4.0, the product and process perspectives are essential as they offer guidance in terms of which technological trends to follow and subsequently what substantial investments to take. E.g. investment in software patents that enable geo-tracking of self-driving cars.

Finally, the network layer shows the necessary structure and characteristics of a future value network that is capable of delivering the intended value proposition. A company may sketch which processes they plan to outsource to which business partners and which other players will have an influence on the process. E.g. a car manufacturer that will need a strong partner in embedded systems development.

Each box in the roadmap represents a state or goal on the way to the ultimate Industry 4.0 vision. Additionally as well a strategy to reach the goal is formulated within the box. Solid arrows represent requirements from the upper to the lower layer whereas dashed arrows represent potential enablers or success factors for the upper layer. The time dimension is indicated by a rough time-frame or a concrete date depending on the overall time horizon of the company.

The output of this stage is a timely ordered and multi-perspective map of the overall strategy towards the envisaged Industry 4.0 vision that builds the strategic frame for concrete actions. The time horizon for realization of the Industry 4.0 vision determines whether a company takes a revolutionary approach versus an evolutionary approach.

3.3 Stage 3: Enact

Finally, the “Enact” stage has the goal of transforming strategies into concrete projects. Thus, project goals, teams and principal milestones have to be defined. Projects are subsequently evaluated and prioritized against the resources available, potential risks and expected impact on the overall mission.

During this stage also projects are included which are currently in progress or under consideration. E.g. a car manufacturer has already launched a project to manufacture electric cars. They are checked whether and how they relate to the newly ideated projects and how they fit into the strategic roadmap resulting from the “Enable” stage. This activity is again conducted in a collaborative manner. Hence, external stakeholders are only involved as far as cooperation is required. Current projects that are considered of relevance for a future Industry 4.0 roadmap are selected and presented by the responsible departments to other stakeholders of the transformation process.

For all projects responsible departments are encouraged to make suggestions about the future integration of the project into the overall strategy and which additional resources are required to fulfill these goals. Projects considered for future inclusion in the roadmap can be both technology oriented projects, organizational change and strategic projects. Alignment of future Industry 4.0 projects with current projects and vice-versa ensures an efficient and sustainable transformation of resources, responsibilities and mindsets in the sense of the Industry 4.0 vision.

The output of this stage – the project roadmap – is finally linked with the previously developed high-level strategies and therefore complements the yet abstract strategic business model perspective with a concrete map of planned activities that can be communicated among principal stakeholders and the wider community.

3.4 Summary

Our process model suggests three stages to develop a company-specific strategic roadmap towards Industry 4.0. It enables a company to clearly communicate its Industry 4.0 vision and strategy internally but also externally towards important stakeholders.

The co-innovation approach along with a systematic visualization of goals, strategies and concrete projects ensures a shared understanding of Industry 4.0, the impact on the company’s structure and processes and the required activities to transform into an Industry 4.0 ready company.

The strategic roadmap is regarded as the central artifact that serves three main purposes:

- As a means to consistently analyze and plan the transformation of business models and assess the impact of technology
- As a means to facilitate collaborative development of vision, strategy and projects
- As a tool to manage and track all activities regarding the transformation process towards Industry 4.0

4 FIRST EXPERIENCES FROM THE FIELD

Our three-stage model is the result of a series of workshop sessions that we conducted in the course of an Industry 4.0 initiative which started off in early 2014 in cooperation with Austrian government and several leading industrial companies and associations. Since that we used the model as a guiding framework for raising awareness of the Industry 4.0 vision in the Austrian industrial sector and to guide companies in their first steps towards preparing for a respective transformation.

Our findings show that developing an Industry 4.0 vision is still a challenging task. Although many executives are aware of the potential of Industry 4.0 related business models and technology they had substantial problems to go a step further and develop their own company-specific vision. Rather they had the expectation that Industry 4.0 is the solution itself. However, our co-innovation approach (→ "Envision") shows that rethinking business models by involving multiple stakeholders is beneficial for a mutual understanding of different developments within and beyond the company's boundaries and led to a commitment for Industry 4.0 to be of strategic importance for the whole company and not only for the production department.

Regarding the phenomenon that companies tend to think Industry 4.0 in terms of technology not and rethinking their business models we addressed this misconception through our strategic roadmapping approach (→ "Enable"). Roadmapping encouraged taking different perspectives during the Industry 4.0 strategy development process and therefore also stimulated a discussion about business models.

The mapping of concrete action points or projects (→ "Enact") against the rather abstract strategy roadmap is the point where the maximum of participation was reached. Within this stage middle management and people from operations got engaged as they were able to present current efforts and as well had the opportunity to present their view. In retrospective, we consider the latter stage the most important one as at this point the entire Industry 4.0 vision and strategy will be validated and, in case it is not well conceived or communicated, will fail.

5 CONCLUSIONS

In this paper we describe a three-stage process model to guide manufacturing companies in transforming into an Industry 4.0 ready company. The process model is based on the concepts of co-innovation and strategic roadmapping and offers a guiding framework for the systematic transformation of a company's vision and strategy towards Industry 4.0 readiness.

The process model is unique as it goes beyond a pure technological view and proposes that the fourth industrial revolution needs a systematic integration of generic Industry 4.0 concepts with company specific vision and strategies as a basis for a subsequent technological transformation of the production system. Our approach extends previous research from Fraunhofer (see [8], p. 588) as it provides a solid methodological foundation for guiding companies in their Industry 4.0 related activities.

Although we have developed the process model on the basis of practical experiences we plan to validate and refine our model through further case-studies in manufacturing companies. In fact, the vision of Industry 4.0 is already on the agenda of most industrial enterprises. Hence, our experiences show a strong interest in methodological support to effectively adopt related concepts.

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7 BIOGRAPHY

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The Development of an EEG Data Management System Using Action Observation Network in Autonomic Wireless System

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Abstract
An integrated system comprising of Action observation network and autonomic wireless system was used in electroencephalographic (EEG) data transmission and management for robotic control. An EEG Action Observation Network (AON) was developed and designed to integrate, manage and transform EEG data into machine readable command code for robotic control. The EEG Autonomic network system exhibited self- managing characteristics and functions. The EEG Autonomic system provided a self-management system in the computational architecture of robotic control system. The EEG information management and transmission system using action observation network in autonomic wireless system is presented in the paper as the high level computing system in EEG data management and transmission network for robotic control.

Keywords
EEG Data Management, Action Observation Network, Autonomic Network

1 INTRODUCTION

Advancements made in wireless sensor networks were aimed at transmitting information effortlessly in widely distributed networks for robotic control. Wireless Sensor Network (WSN) applications in bio-signal transmission significantly facilitated the development of EEG data management. The EEG data management process using WSN optimized bio-signal conditioning and often reduced the care and cost of managing the bio-signal acquisition process. EEG electrodes placed at the scalp, in the brain or on the skin constituted part of the EEG wireless sensor network development. Each EEG electrode formed a network node for receiving and transmitting bio-signals. Due to the low cost and power consumption of the EEG technology, it opened possible application avenues for industrial process controls and robot navigation [1]. WSN specific performance features can allow specific electronic devices to efficiently transmit and receive bio-signals [2]. Integration of microcontrollers, sensors and transmitter-receiver modules formed the basic architecture for the WSN. The energy consumption needs and processing capacity of the WSN provided insights into the efficiency of the WSN. Wireless sensor networks are classified according to the applications and functions of the sensing technology. Robot motion responsiveness determines the application and use of each of the wireless network application and classification.

The EEG Action Observation Network (AON) was designed to integrate and transform observed cognitive processes and thought processes originating from EEG signals into machine readable command codes. Due to its design, nature and characteristics, the AON responded to specific EEG signals [3]. The network was designed to automatically respond to the presence of EEG artefacts transmitted in the autonomic wireless system. Cognitive processes such as eye blinks, facial expressions and imagination of motion of interest activates AON. The effective management of cognitive load on AON led to effective robotic and mechatronic system control. Behavioural activities capable of transforming cognitive activities into useful artefacts were of importance in the control of semi-autonomous mechatronic systems using autonomic neural network architecture. The matching of cognitive and behavioural activities played critical role in the optimisation of AON in the autonomic wireless system. The preferential engagement of robotic motion or mechatronic system control showed that observed activities were critical in the development and optimisation of the AON [4]. Activities of interest within the familiarity continuum may be seen as part of the wider indicators of activators of AON. In the design and functional characteristics of the EEG data management system, AON can be activated by a wide variety of social behavioural and cognitive activities.

The focus of the paper is on the development of EEG data management and transmission system using AON and autonomic wireless system for robotic control. It is not in the purview of this paper to delve into the number of participants involved in acquiring EEG data and the type of electrode used in acquiring the EEG data.

2 THE AUTONOMIC WIRELESS SYSTEM

The EEG Autonomic wireless system is a system that is capable of exhibiting self-managing characteristics and functions. The autonomic system provided self-management characteristics in the computational architecture of control systems used in robot development. The EEG information management and transmission system is a high level computing system developed to manage and transmit EEG data. The high level computing system was void of human effort in the running and operational maintenance of the network. The EEG autonomic wireless system provided robust data management and transmission application. Automatic subdivision for information management and transmission introduced in the EEG autonomic wireless system eliminated the need for human involvement in the maintenance of the system. The development and design of the autonomic wireless system was inspired from the functioning of the human nervous system. Considering that EEG data originated from the brain and formed part of the nervous system, it was worthy to develop and implement the autonomic wireless system with minimal human intervention. The EEG data management system utilized the principles of autonomic computing in managing the information transmission in an adaptive neural network [5]. The sole purpose for the EEG autonomic wireless system development was to have an EEG data management system that was self-adaptive, self-healing and self-managing. The design of the EEG autonomic wireless system presented high level complex distributed computational architecture shown in figure 1 for self-managed EEG information transmission. The EEG autonomic wireless system was developed while considering five different data management and transmission processes. These included:

- **Basic Level:** In this system, the system operator managed the EEG data transmission from setup to decommissioning manually for entire life cycle of the mechatronic or robotic system.
- **Managed Level**: In this system, the system operator utilized the available EEG data transmission and management technologies to monitor multiple information outputs from EEG data simultaneously. This was done with adequate human machine interfaces or BCI.
- **Proactive Level**: Sensor information was utilized to provide analytical solutions leading to proactive decisions. Warning systems were used to propose solutions to the operator.
- **Adaptive Level:** In this level, the mechatronic or robotic system collected information from the environment and was able to predict and react autonomously without human assistance. The specification of actions in the possible scenarios required situational judgment for lower level decision making and actions.
- **Autonomic Level:** In this system, it was expected that the interactions between the human nervous system and machines were constructed on high-level objectives and functions. The high-level information policies were encoded in the network architecture and the system responded in accordance to the interpretations of the policies.

In developing the wireless autonomic network system, it was critical to identify the autonomic network computing characteristics. The associations in the autonomic network initiatives were identified with the aim of fulfilling its objectives. The key objectives for the autonomic computing architecture were self-configuration, self-optimisation, self-healing and self-protection. Figure 2 shows an RN-171-XV wireless module and figure. 3 shows an X-bee Pro wireless module. These two wireless modules were used in the design architecture of the autonomic wireless system.

2.1 The Autonomic Wireless System Design Principles

Two RN-171-XV and two X-bee Pro wireless modules were used in the implementation of the EEG wireless autonomic neural network system. The principles on which the EEG autonomic wireless system was modelled was based on the mode of information exchange similar to the human nervous system. The properties exhibited by the human nervous system during information transmission were valuable in determining the survivability of the autonomic wireless system. The mutual behaviour of the subsystems in the EEG autonomic wireless system were used to determine valuable network properties. These properties included:

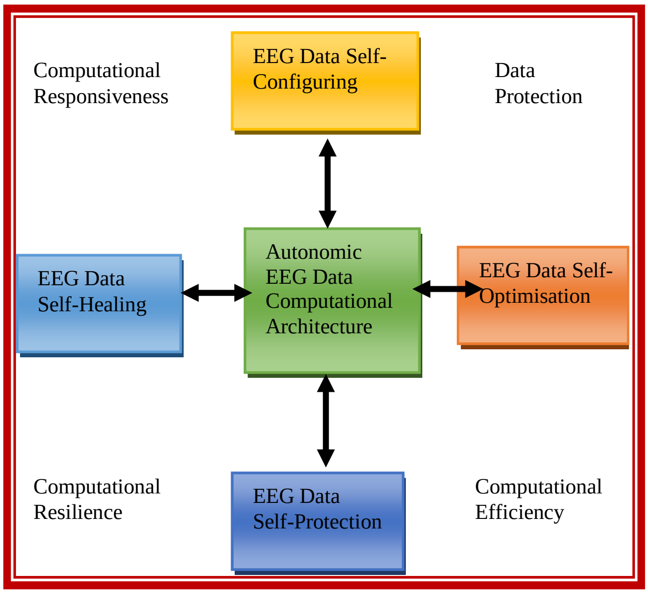

Figure 1 - Autonomic EEG Data Computational Architecture

Figure 2 - The RN-171-Wirelss Module

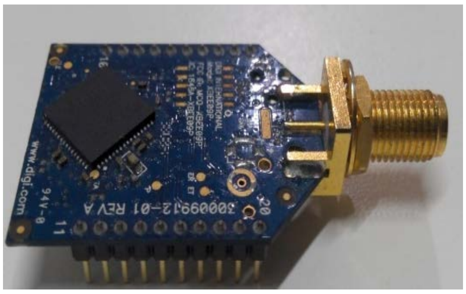

Figure 3 - The Xbee-Pro 900MHz Wireless Module

- **Network Survivability:** The EEG network internal mechanisms were continuously matched to generate essential network variables which were within the limits defined by the EEG data transmission thresholds. The adaptive functionality of the network subsystems were the key ingredients to the survivability of the EEG autonomic wireless system. When there were external stimuli requiring transmission of mega data, the system readapts and readjusts its working mechanisms in order to maintain the specified data transmission viability region. The adaptation mechanisms played important role in the survivability of the EEG autonomic wireless system.
- **Mutual Behaviour:** The collective performance of the autonomic wireless subsystems influenced the overall performance of the EEG autonomic wireless system. Local information transmission challenges became the global determining factors influencing the network behaviour.

In figure 4, the global strategies of the autonomic network system is shown and in figure. 5 the wireless architecture integration in the autonomic structure is shown.

3 ACTION OBSERVATION NETWORK

The EEG Action Observation Network (AON) was developed in order to transform EEG signals into machine readable command codes for robotic control. The network characteristics of the AON responded to EEG signals [3]. The AON was developed and designed to automatically respond to the presence of EEG artefacts in the autonomic wireless system. The intent, imagination of motion movements, thought processes and cognitive processes of interest activates AON. The kinetics and mechanics of observed actions, learned actions and imagined actions showed the importance of brain familiarity in generating the required EEG artefact for controlling mechatronic systems. It was evident that there was the need to code similar neural processes associated with the observed behavioural actions. These were mapped to the neural sites generating the EEG signal [13]. Transforming cognitive activities into useful artefacts were of importance in the control of semi-autonomous mechatronic systems in the autonomic wireless network architecture. The influence of physical activities and movements on brain activity modulation was observed to affect the activation of specific neural site or brain lobe. Regular observation of activities and physical processes in the environment has been carried out both consciously and unconsciously without any specific motive [14]. In this study, having specific aims and objectives while observing physical activities created untapped neural resources in the development of BCI technology.

Predictive cognitive mechanisms were fundamental to the effective integration of AON in autonomic neural network. It can be concluded that perspective, aim and transitivity when directed and coordinated adequately influenced the generation of EEG artefacts from specific brain regions. In order to effectively portray the concepts embedded in action observation network, it was noteworthy that action observation mechanisms were products of the cognitive activity type and sensory processes in the primary motor regions. The simulation of actions, activities and tasks were fundamental to the common performance of the autonomic neural network substrate [15] [16]. The integrative approaches presented in the study were intertwined with the various segments of the BCI and were reliant on sensory motor performance and articulation. With predictive coding, observed actions were simulated facilitating the modulation and increased the efficiency of AON system.

In order to effectively control the mechatronic system, the AON system was trained to recognise certain actions when viewed or imagined. The observation of actions, activities, signs and the imagination of such behavioural and cognitive activities was the key to AON functional mechanism [10]. Close correlation and optimisation of behavioural activities to cognitive activity and load were not easy to correlate. The relationship was difficult to establish as it was not easy to isolate behavioural observation and purely imagined activity. It was imperative that BCI users acquainted themselves with behavioural activities and actions that are able to effectively activate AON. Visual inputs and imagined actions provided cognitive representations that evoked the potentials necessary and required in the control of robotic and mechatronic systems. Learning and training were critical processes of the EEG data management technology development. Adaptive learning in the AON autonomic system was proposed during the study. Adaptive learning in this study referred to the state where the AON autonomic system recognized observed patterns and actions acquired from the EEG artefacts. These activities were translated in the quickest and most accurate form irrespective of subject behavioural characteristics [11].

Behavioural pattern recognition in EEG signals representations were important especially in passive stimuli translation. Several neural sites responded to these observed behavioural activities in conjunction to physical training of motion movements. Interactions with objects and devices with our immediate environment stimulated neural responses [12]. The stimulation of neural responses activated AON for use in the control of semi-autonomous mechatronic systems integrated in within autonomic neural network system. The kinetics and mechanics of observed actions, learned actions and imagined action are necessary in generating the required EEG signal for controlling mechatronic systems. It was crucial that the desired neural processes were activated in the observed behavioural actions [13]. The pragmatic translation of the behavioural activities and imagined actions across the autonomic neural network and AON created an efficient technique in the correlation of cognitive activity to robotic motion.

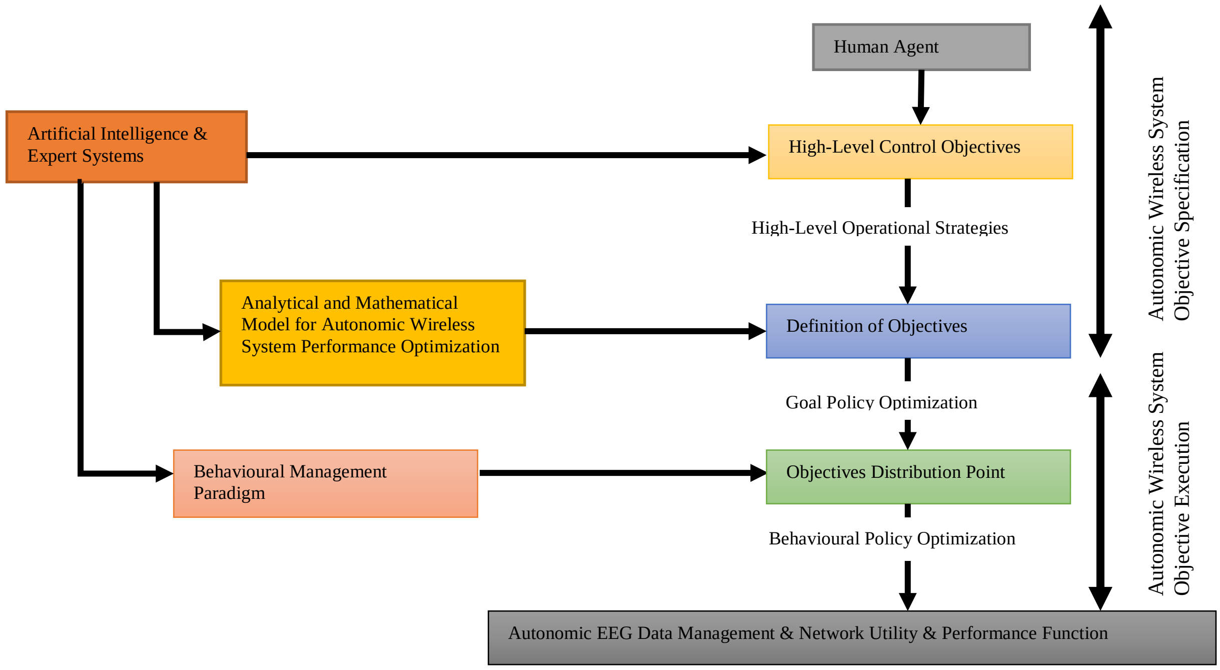

Figure 4 - Global View of Autonomic Wireless Structure

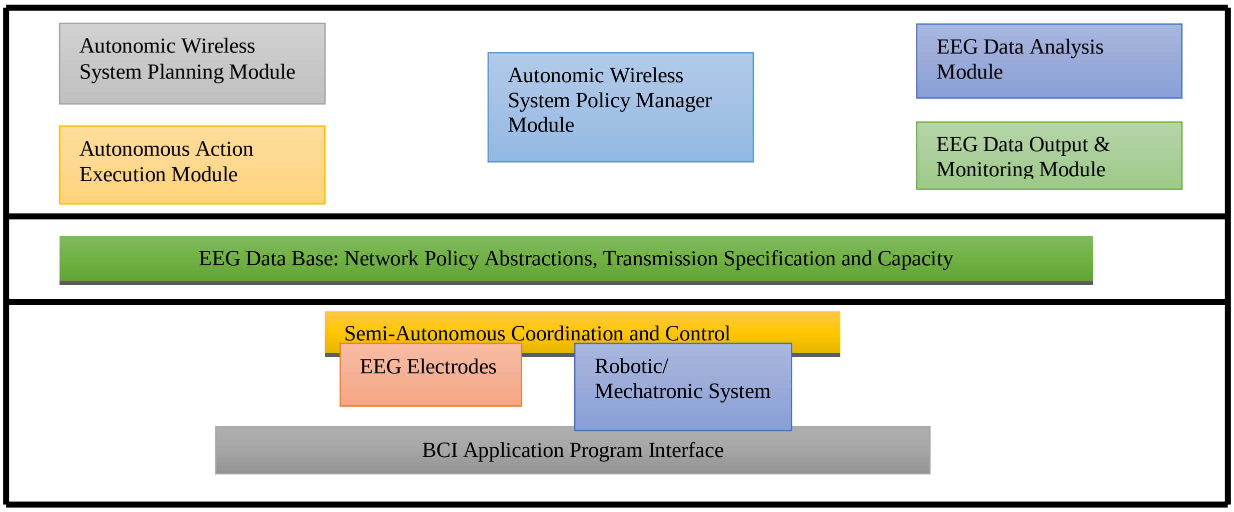

Figure 5 - The Autonomic Structure for Autonomic Transmission.

4 SYSTEM INTEGRATION

The system integration setup for the study included recorded EEG data which were assumed to be free of any neurological complications. Microelectrodes were used in the recording of electrical signals from the brain. This provided means of measuring relatively high spatial and temporal resolute electric discharge patterns. It also provided the desired technique for analysing and observing the functional behaviour of neurons and the transmission of EEG signals in autonomic neural networks towards developing robot control commands. The two RN-171-XV and two X-bee Pro wireless modules were used in transmitting and receiving the EEG data wirelessly. The Emotiv and Neurosky EEG headsets were used in acquiring the EEG data.

The filter which was used in the management of EEG signal for feature extraction was the finite impulse response (FIR) filter. The FIR filter computed EEG signal out as weighted finite sum of raw EEG signal as inputs into the filter. The working mechanism of the FIR filter was centred on the feed-forward principle for feed-forward neural networks. The FIR filter provided robustness for the AON and autonomic networks used in the management of EEG signal. This was attained through the computational efficiency of the FIR in both recursive and non-recursive neural network realization. The FIR filter has minimal noise output. The computational errors and sensitivity to variation in filter coefficients were also minimal [18]. The FIR filter was modelled as [19]:

$$y[n] = \sum_{k=0}^{N-1} b_k \cdot x[n-k] \qquad (1)$$

Where $y[n]$ represented the FIR filter output, b_k represented the FIR filter coefficients, N represented the number of FIR filter coefficients required in EEG signal analysis and $x[n]$ represented input to the FIR filter from raw EEG signal. The FIR filter specification was given as [19]:

$$x[n-k] = \begin{cases} 1 & for\ n = k \\ 0 & for\ n \neq k \end{cases} \qquad (2)$$

The model for the filter integration with other autonomic network sub-systems are shown in figure 6.

5 NETWORK PERFORMANCE EVALUATIONS

The performance of the wireless autonomic EEG network was evaluated using the Bit Error Rate (BER) for the wireless EEG data transmission. The EEG data was passed through Additive White Gaussian Noise (AWGN) using flat Raleigh as the fading channel. The performance was evaluated using the AWGN as the reference point. The result indicated in figure. 7 show that the lower the SNR of the EEG wireless network, the higher the probability of error in the transmission of EEG data across the autonomic wireless network and vice-versa.

An adaptive linear equalizer was used in evaluating the channel transmission performance for the RN-171-XV wireless modules and X-bee Pro wireless modules in transmitting EEG data over the autonomic wireless network. The results from the linear equalizer indicated that the network BER reduced as the SNR of the network increased to 20 dB and stabilised thereafter. The wireless network taps were influential in the lowering and increasing the BER for the network. The wireless EEG network taps were indications of feedback sequences required to overcome EEG signal interference. The higher the network taps, the more unstable the wireless autonomic transmission of EEG data. In figure 8 the throughput results of the effects of the adaptive wireless network equalizer on EEG data transmission over autonomic network is shown.

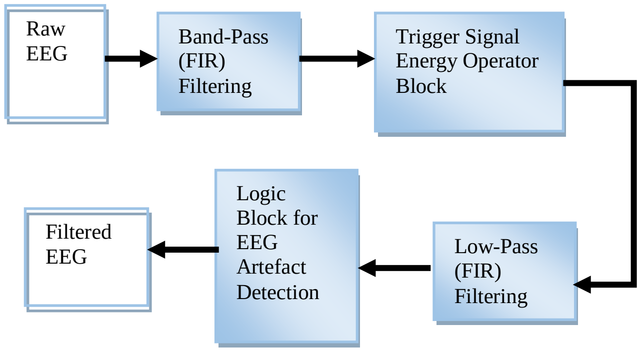

Figure 6 - Filtering Model for the Raw EEG Filtering

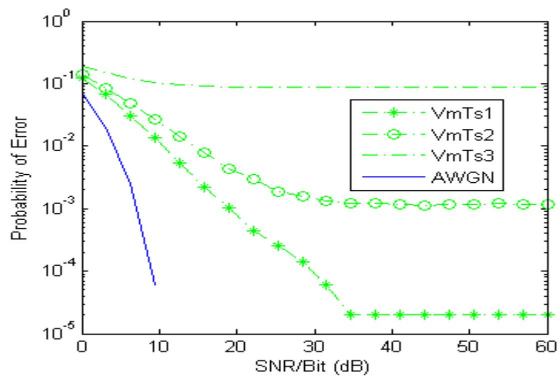

Figure 7 - EEG Wireless Autonomic Network Bit Error Rate Performance Throughput

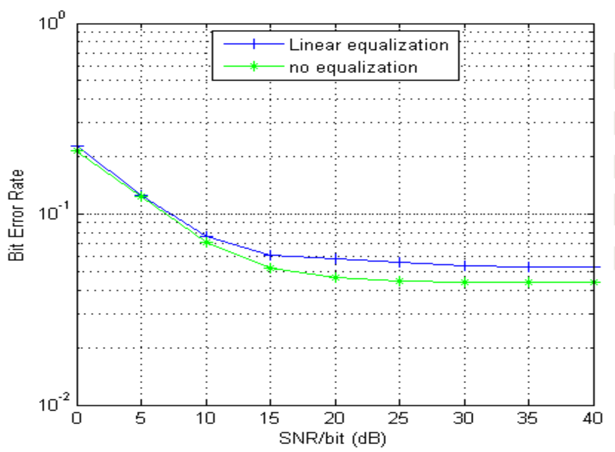

Figure 8 - Adaptive Linear Equalizer on Wireless Autonomic Network Transmission

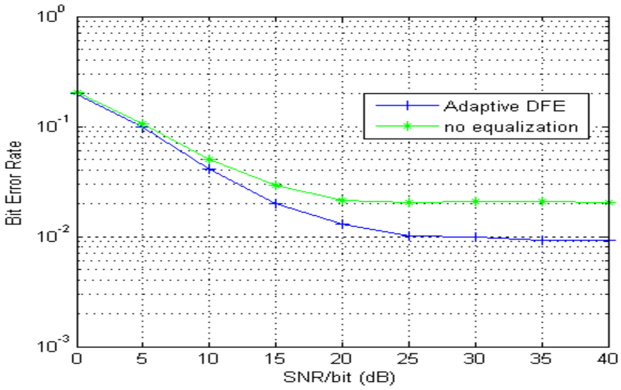

Figure 9 - Autonomic Wireless Decision Feedback Equaliser Throughput Performance

In figure 9, results from the autonomic wireless network decision feedback mechanism is shown. The throughputs from the autonomic wireless network show that coherent demodulation of the wireless network decreased the BER of the wireless network given that the network data transmission phase was in perfect synchronization.

Increasing the signal path loss parameter of the EEG autonomic wireless network resulted in fewer EEG data being managed by the wireless autonomic network. Lowering the signal path loss parameter enabled the autonomic wireless to manage more EEG data efficiently. The results the signal path loss analysis include the signal amplitude peaking at 0.7 for a higher signal path loss and the signal amplitude peaking at 1 for a lower signal path loss. The transmission efficiency of EEG data was influenced by the wireless network path loss parameter.

6 CONCLUSION

The paper discussed the development and integration of EEG data management system using AON in autonomic wireless system. The action observation architecture ensured that information and data from EEG signal source were matched to signal outputs within the autonomic wireless system for use in the control of mechatronic or robotic system.

The relationship between cognitive task and intended robot control commands are established using the AON augmented in the EEG autonomic wireless System. The EEG data management system was evaluated using the autonomic wireless system bit error rate (BER) and the system equalization properties. The autonomic wireless system relied on the effective management of EEG data and the placement of EEG electrodes on the scalp.

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Resource-based Reconfiguration of Manufacturing Networks Using a Product-to-plant Allocation Methodology

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Abstract
Given today's demand for product variants in different market segments, manufacturing companies are facing high degrees of complexity when utilising existing global manufacturing networks. To remain competitive, reallocating production of product variants according to their lifecycle becomes essential in order to use resource capacities more efficiently. Therefore, companies must take into account costs and benefits of standardisation and specialisation of their production facilities to meet long-term corporate goals. An approach for allocating products to plants is sought that addresses the stated matters by allowing for reconfiguration of production networks, determining optimal flexibility levels of production facilities, and taking strategic guidelines into account. In this paper, a resource-based approach is introduced in which product variants and production resources are mapped to production processes in order to determine optimal configurations of the manufacturing network while considering restrictions. The approach will be applied to the final assembly of a large scale products' manufacturer.

Keywords
Manufacturing Networks, Reconfiguration, Product-to-plant Allocation

1 INTRODUCTION

Determining ideal structures of production networks poses a challenging task for manufacturing companies nowadays. In order to gain competitive advantages, companies seek to distribute their production activities globally. By doing so, manufacturing companies can capitalise on factor cost differences or meet local customer requirements in a superior way compared to an export-oriented strategy [1]. Companies therefore have to allocate production volumes of products to different production plants. Besides this global dimension of manufacturing, demand for products has significantly evolved during the past decades. In order to meet today's customer requirements, manufacturing companies have continuously increased the number of their offered products and product variants [2]. Since providing specialised production facilities for each individual product or providing production facilities compatible with the entire product portfolio can incur prohibitively high costs or poor resource utilisation, manufacturing companies have to determine the optimal level of standardisation and specialisation regarding production facilities [3]. Furthermore, since demand for products and location factors are subject to uncertainty, manufacturing companies need to implement measures to adapt to varying circumstances [4]. Abele et al. (2008) observe that production networks can exhibit "legacy structures", which have been expanded gradually without holistic and strategic planning. Such structures can result in poor resource utilisation and low service levels [1].

Given the mentioned challenges, a holistic approach for strategic and tactical planning of manufacturing networks is presented in this paper. The approach can be utilised to derive production network configurations with regard to the objectives of a particular company. Throughout this process, currently available as well as potentially available resources in terms of machines and staff can be deployed. Modelling production on resource level allows a capitalisation of the entire potential of existing resources with their individual properties. Besides, distinctive production technologies representing different levels of automation or different production techniques are considered. By applying the approach, a product-to-plant allocation strategy can be determined. The assignment is conducted on process level so that the value creation of products can be distributed among different sites. Throughout this approach, local production capabilities and resource capacities are mapped to product characteristics based on their relevance for production. Since determining factors for production network configuration evolve over time, time-variant data can be used for factors that are prone to changes. Hence, a particular configuration of a production network may only be optimal for a limited time span. The approach is therefore dynamic and allows for reconfigurations of production networks at multiple points in time. Besides the mentioned properties, the approach considers flexibility of production facilities in terms of compatibility to different products.

2 FOUNDATIONS

2.1 Planning tasks in production networks

Establishing and operating global production networks encompass several planning tasks with distinctive focal points. [5] propose a hierarchical scheme for classifying planning tasks in production networks using two dimensions. As illustrated in Figure 1, all planning tasks are assigned to a certain level of planning and a certain planning object. Concerning levels of planning, tasks can address production on network, site, and line level. Planning objects of a certain task can be structures, capacities, and orders. Determining structures, capacities, and orders relates to strategic, tactical, and operational planning respectively.

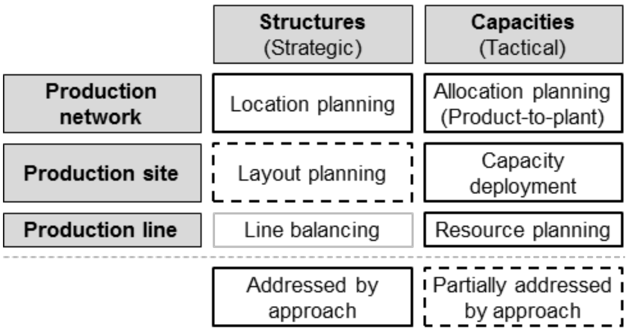

Figure 1 - Classification of planning tasks [5].

The presented approach mainly addresses strategic and tactical planning of capacities and structures, namely location planning, (product-to-plant) allocation planning, capacity deployment, and resource planning; layout planning is partially covered. By addressing these tasks, the entire potential of available and potential resources can be considered, while taking into account characteristics of products and production locations for advantageous product-to-plant allocations.

2.2 Flexibility and transformability

Companies are able to react to changing demands and other circumstances by adapting its structures, capacities, and processes on different levels. For the presented approach, the concepts of flexibility and transformability are of particular interest.

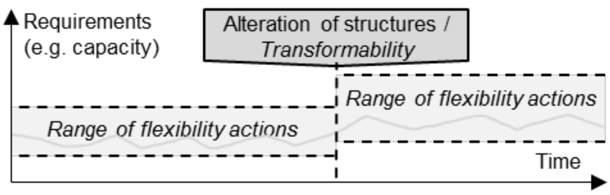

Figure 2 - Flexibility and transformability [6].

Even though many different definitions of flexibility have been stated, flexibility of manufacturing companies commonly refers to the capability to adapt within a certain predefined range of actions without altering basic structures of production networks. Such adaptions can be conducted in short time at low cost [7].

Transformability is understood by many researchers as an expansion of flexibility. The range of actions determined by the boundaries of flexibility can be dispersed by means of transformability. Therefore, transformability refers to the potential to alter structures in terms of technologies, staff, logistics, and organisations at low capital expenditures. As depicted in Figure 2, altering structures redefines the boundaries of flexibility and therefore the range of future actions related to flexibility [7].

The presented approach is based on the stated understanding of flexibility and transformability. Flexibility is related to a given configuration state of a production network and refers to adaptions within the given structures. Transformability on the other hand is related to the process of reconfiguration, which represents the transition of a production network from one configuration state to another configuration state. In this process, structures are altered and boundaries for future flexibility are redefined.

Several types of flexibility have been identified in literature reviews [8, 9]. Product-mix flexibility, routing flexibility, and volume flexibility are implemented in the presented approach. Product-mix flexibility describes the quantity of different parts or products that can be produced without requiring expensive set-ups between processing two products. Routing flexibility describes the number of feasible routes for products through a production system. Volume flexibility refers to the ability to vary production output of production systems while asserting profitable operation, e.g. using shift models.

Chaining represents a flexibility concept based on product-mix flexibility. Jordan and Graves (1995) conclude that configurations of production networks exhibiting pairwise product-plant compatibilities so that compatibilities constitute a chain among products and plants are almost as resilient to stochastic demand variations as networks exhibiting full flexibility [10]. A fragmented value chain can cope efficiently with varying demand, if chaining structures are established for every process [11].

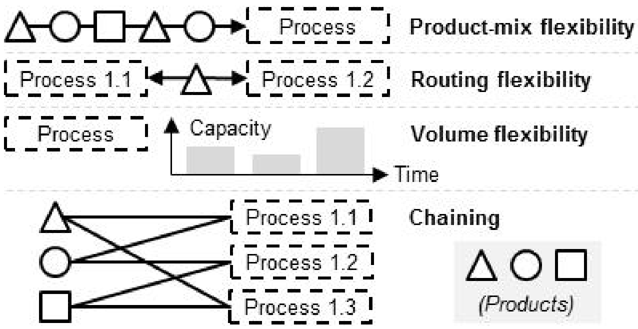

Figure 3 - Implemented flexibility measures.

Transformability allows alterations of a production network's structure. The characteristics universality, mobility, scalability, modularity, and compatibility of elements are widely considered as primary enablers of transformability [12]. The execution of reconfigurations in this approach is based on these enablers. Mainly, universality, mobility, and scalability of certain elements are specified, while modularity and compatibility are assumed to be available at a sufficient extent to support proposed reconfigurations of the production network.

3 EXISTING APPROACHES

Most existing approaches on reconfiguration of manufacturing networks feature modelling on plant or production line level, whereas few approaches such as [13, 14] include modelling of specific resources. Several product-to-plant allocation schemes such as [15] have been stated. However, most of these approaches do not consider product characteristics and capabilities of production sites. In order to take into account varying determining factors for configuration of manufacturing networks, [16] for instance has introduced a dynamic approach. Flexibility is widely addressed in literature [3, 7, 8, 10]. The presented approach is intended to cover all mentioned aspects of planning holistically.

4 RESOURCE-BASED RECONFIGURATION

4.1 Scope and application

To foster strategic and tactical planning of production networks, the underlying modelling approach covers structures and capacities in production and logistics of manufacturing companies. Material required for production, storage processes, and inventories are not intended to be key areas of the consideration and are therefore not explicitly modelled. Production infrastructure is considered on network, site, production line, and work station level. The approach is cost- and capacity-oriented, while lead times are also considered.

The approach has been developed for manufacturing networks used for production of large-scale, durable products such as aircraft, rail vehicles, or lorries with numerous configuration options for customers. These products are typically produced in small and large series by means of flow production in a non-continuous setting [17]. Due to comparatively low production quantities and relatively high effort induced by movements, unfinished products are commonly processed for several hours at an individual workstation. In some cases, product dimensions and weight restrict the mobility considerably. The approach was specifically developed for the mentioned industries with its properties, yet it can be used in further industries with similar characteristics.

Concerning planning situations, the approach has been developed for reconfiguring a "legacy" network. However, it can be used for multiple greenfield and brownfield planning situations faced by manufacturing companies.

4.2 Basic modelling elements

As illustrated in Figure 4, resources to be modelled are sites, machines, and staff all exhibiting certain characteristics. Products require certain processes with specified capacities for completion. Processes can be realised by certain technologies. In a given configuration, machines and staff are deployed to sites and are used for processes necessary for completion of products. The allocation of machines to processes is fixed within one configuration, whereas staff can be shifted among processes within one site. Besides the stated modelling elements, transports are essential for value chains that are distributed among several sites.

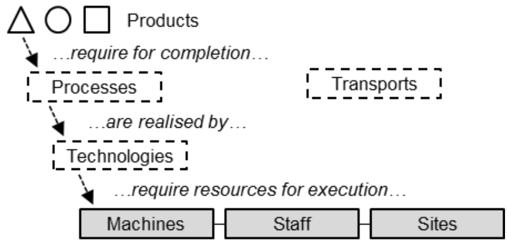

Figure 4 - Modelling elements.

Processes represent "black boxes" of production processes which are specified in terms of input and output, while the actual transition is unspecified at this stage of modelling. Technologies on the other hand describe transitions by specifying required capabilities of machines, qualifications of staff, and implicit knowledge. Processes allow an abstract view on production activities, without considering technical details [14].

4.3 Attributes of modelling elements

Cost is a generic attributes of all resource types; the resource types exhibit fixed and variable cost as well as resource-specific costs. Salaries are considered fixed costs due to labour union agreements typically present in manufacturing companies. Machines in addition bear variable cost in terms of costs per machine hour. The required area demand of machines for their placement can be met by sites that provide a certain area. Machines and staff are deployed at certain locations (sites). Staff and machines offer a certain number of labour hours and machines hours respectively. Staff can be distinguished by different qualifications. Also, employees can receive training to gain further qualifications. Since the approach is dynamic, resource attributes can be defined as time-variant input. Furthermore, attributes of the same resource may vary at different sites reflecting different levels of factor input costs.

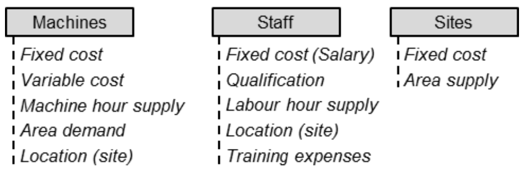

Figure 5 - Resource attributes.

In case of several technologies being available to realise processes, one discriminating characteristic of different technologies may be the level of automation. Technology matrices contain information about required machines and qualifications of staff to deploy a certain technology for process execution. Figure 6 depicts an exemplary situation involving two distinctive technologies that can both be used to realise process 1:

Process 1	Technology 1.1	Technology 1.2
Machine 1	✓	
Machine 2		✓
Qualification 1	✓	
Qualification 2		✓

Figure 6 - Technology matrix.

Technology matrices do not contain quantitative information about machine and labour hours required for processing of products since these hours are dependent on the processed product and the deployed technology. Exemplary demands for a product in process 1 are depicted in Figure 7:

Process 1 △	Technology 1.1	Technology 1.2
Machine hours	50 h	10 h
Labour hours qualification 1	5 h	
Labour hours qualification 2		40 h

Figure 7 - Machine and labour hour demand.

Technology 1.1 could represent a production technique involving a higher level of automation than technology 1.2 indicated by different ratios of required labour hours to required machines hours.

In order to implement value chains with job content distributed among several sites, unfinished products need to be transported among sites. Transports incur transportation cost and bear transport times.

4.4 Decision space for reconfiguration

So far, attributes that are relevant for a given configuration of a production network have been considered. In order to reconfigure production networks, the decision space consisting of resource-related actions has to be defined.

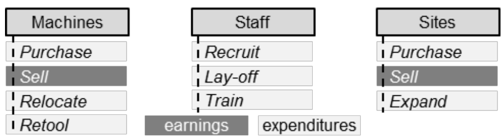

Figure 8 - Resource actions at reconfiguration.

As depicted in Figure 8, feasible resource-related actions that apply to all three resource types are purchase and sale as well as recruitment and lay-off respectively. Machines can be relocated to a different site and be retooled so that they are compatible to other technologies. Sites can also be expanded. The decision space regarding the three resource types has to be defined by specifying the mentioned discrete actions for all existing and potential resources. Every action is linked to expenditures or earnings in financial terms. Existing resources must be specified explicitly while potential resources can be represented by marginal costs for one additional unit of capacity.

4.5 Dynamic workflow of the approach

The approach can be applied to a time span specified by the user. The time span has to be subdivided into discrete time periods of equal duration. Since the approach addresses tactical and strategic planning tasks, several years typically constitute the time span, while time periods may last for weeks or months.

Due to varying determining factors for manufacturing networks, configurations of production networks might only be optimal for a limited amount of time. Therefore, the approach allows specifying the frequency of potential reconfigurations. Reconfiguration between two time periods is enabled by transformability of resources and need to be in line with the previously defined decision space. The remaining time is referred to as operation. In-between time periods without reconfiguration, the production network is able to adapt by means of the presented flexibility measures.

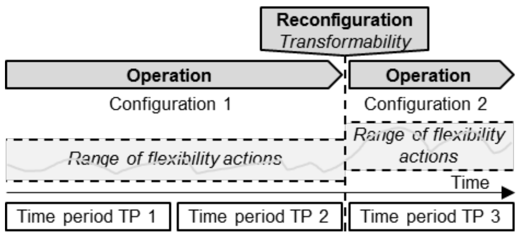

Figure 9 - Operation and reconfiguration.

4.6 Target function

In each period of operation (t) different costs accrue. The cost of operation in one specific time period (OC_t) consists of operating cost of sites (OCS_t), staff salaries (OSC_t), machine cost (OEC_t), and transport cost (OTC_t):

$$OC_t = OCS_t + OSC_t + OEC_t + OTC_t \qquad (1)$$

Besides accumulated cost for operation during considered time periods, expenditures or earnings arise from reconfigurations between two time periods. Reconfiguration expenditures between two time periods (RC_t) consist of purchase prices of sites ($RSPC_t$), recruiting cost for staff ($RSRC_t$), lay-off cost ($RSLC_t$), training expenses ($RSQC_t$), machine relocation cost ($RETC_t$), purchase prices of machines ($REPC_t$), and machine retooling cost ($RERC_t$) subtracted by sales proceeds from sites ($RSSP_t$) and sales proceeds from machines ($RESP_t$). The indexed time periods (t) refer to the time period after the configuration:

$RC_t = RSPC_t + RSRC_t + RSLC_t + RSQC_t + RETC_t + REPC_t + RERC_t - RSSP_t - RESP_t$ (2)

By applying the approach, the total sum of operation costs in all time periods and reconfiguration costs for all reconfigurations is to be minimised, while resource capacities are assigned so that the intended production program can be realised.

4.7 Product families and technologies

Manufacturing companies nowadays offer a large variety of products and product variants. Taking into account each individual product in the course of the application of the approach would require a significant effort in terms of data gathering and computation time. In order to keep the quantity of considered products at an appropriate number, products can be grouped into product families. In the presented approach, identical sequences of processes for products represent the first criterion for a product family. Technical similarity reflecting similar requirements in terms of production capabilities represent the second criterion for forming product families. Hence, product families represent homogenous requirements in terms of production capabilities [18].

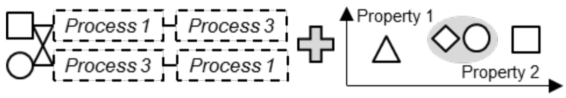

Figure 10 - Product family formation.

Based on this reasoning, products might require the same sequences of processes for completion, but may exhibit differing technical properties. Therefore, different technologies may be needed for processing. For instance, different pieces of metal may both be hardened, but may require different hardening temperatures provided by different ovens. This discrimination of technologies is necessary in order to maintain an unbiased view of inputs and outputs on process level without having to consider technical details.

4.8 Technologies and strategy

Certain technologies might be considered core competencies of a manufacturing company. A company may want to centralise core competencies at one site or may be prudent of moving core competencies to sites overseas. To reflect such strategic considerations, technologies can be restricted to certain sites.

4.9 Production line structures

Due to physical properties of products and sites, the flow of products through production may be restricted to certain patterns. For instance, a longsome production hall with a production line consisting of several work stations for aircraft assembly may only be accessible for aircrafts at the beginning and the end of the production line. Hence, aircraft have to traverse all work stations of the production line whether or not processing is necessary.

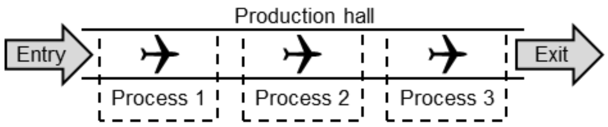

Figure 11 - Restricted flow of products.

In order to implement physical restrictions to the flow of products, certain line structures can be predefined. These line structures dictate fixed sequences of processes that are imposed by physical properties of products and sites.

If a product is not processed at a workstation and cannot move to a different workstation for spatial reasons, it causes idle times at the deployed machines. Such a situation typically occurs in flow production of large-scale products. Idle times occur in production lines used by different products that need to be processed at different sets of work stations. The accumulated idle times of machines represent a loss of efficiency for example incurred by product-mix flexibility of production lines. Such idle times do not occur in production lines that are solely used for production of a single product. Waiting hours of machines on the other hand occur, when products are processed at a work stations, but the corresponding machines are not used during the entire time of processing.

4.10 Lead time considerations

Besides operation cost and reconfiguration cost, the lead time of products through the production network may also be considered. The overall average lead time of an individual product in a time period ($TALP_{pdt}$) is determined by its retention time in production processes and by the transport time ($ATTP_{pdt}$). The retention time consists of idle time in processes ($AILTP_{pdt}$) and lead time of actual processing ($ALTP_{pdt}$):

$$TALP_{pdt} = ATTP_{pdt} + ALTP_{pdt} + AILTP_{pdt} \quad (3)$$

4.11 Implementation

The introduced approach can be represented by a linear discrete optimisation problem. Integer variables can represent most variables of the problem. Variables containing cost or capacity may take non-integer values. However, the set of values is always finite. Hence the problem can be described as a linear discrete non-integer problem which can also be interpreted as a constrained mixed integer linear programming (MILP) problem, whereby instead of being continuous, variables are partly restricted to finite sets of non-integer values. The approach is intended to be implemented in IBM ILOG CPLEX ®.

The functionality of the approach will be demonstrated in the final assembly of a large scale products manufacturer. Product-to-plant strategies and optimal reconfigurations including costs, lead times, and distribution of production volumes will be derived by deploying production resources more efficiently.

5 ACKNOWLEDGEMENT

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7 BIOGRAPHIES

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Systematic Generation and Evaluation of Energy Data in Manufacturing

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Abstract

Nowadays, topics like the climate protection and the associated international and national environmental targets become the center of interest of manufacturing companies. Furthermore, energy-intensive industries pursue a reduction of the energy costs by energy efficiency in order to enhance their competitiveness in comparison to industries with low energy costs. To determine the best efficiency measures, energy transparency and knowledge about necessary data are key requirements. Actually, there are no standards regarding measurement technology or automated data processing to evaluate energy efficiency measures. An intuitive and automated extraction of process-specific load profiles from raw data of an energy demand measurement is not possible. This paper shows how to generate and analyze energy data systematically. The main emphasis is placed on the combination of energy consumption data and machine data as well as the use of a pattern recognition to be able to evaluate technical energy efficiency measures on production systems.

Keywords

Energy Efficiency, Machine Tools, Energy Measures

1 INTRODUCTION

Climate protection is an important political issue of a global dimension. This can be exemplarily seen in the new climate protection targets of US president Barack Obama [1] as well as in the German paradigm shift concerning its energy supply [2] including the change in energy supply by using regenerative energy [3], [4]. The resulting international and national pressure to reduce the environmental impact has arrived in manufacturing companies. In this context, especially energy-intensive industries pursue an enhancement of their competitiveness by energy efficiency measures.

To realize this, it is necessary to have consolidated knowledge about energy consumption in manufacturing. The knowledge, which is aspired, depends on the current enterprise level. At the management level, it is generally sufficient to know, which energy costs will be incurred and e. g. how efficient the sites or segments of the company are in comparison to the competitors. In contrast, a production supervisor, who has to raise the energy efficiency of his machine tool, needs much more detailed knowledge. But for this purpose, energy data by itself are not sufficient, because they cannot be interpreted.

For example, if the energy demand of a production system should be assigned to several cost centers, the sequence of the different processes must be known. Figure 1 shows a load curve of a machine tool machining two workpieces with a standby break of approx. 10 min in between.

To carry out energy analyses efficiently, the questions concerning which data must be acquired and with which precision must be answered in advance. Also the exact measurement sections have to be defined. Furthermore, it must be defined, if the measurements have to be of chronological synchronism.

2 STATE OF THE ART

According to [5] the major constraints for manufacturing companies to conduct energy analyses are the following:

- no standards for measurement technology and data processing
- missing knowledge, which analyses are necessary
- large effects in manpower and time for installation, manual analyses and visualization
- no simultaneous acquisition of machine, operating and energy data

There are numerous scientific publications, which deal with the energy consumption in manufacturing. They can mostly be classified in modeling and simulating the energy demand [6], the integration of energy data in planning and control systems [5] and the investigation of the energy flexibility of manufacturing companies [7] as well as single machines [8]. However, these works take the required energy data as given and do not deal with the generation of energy data.

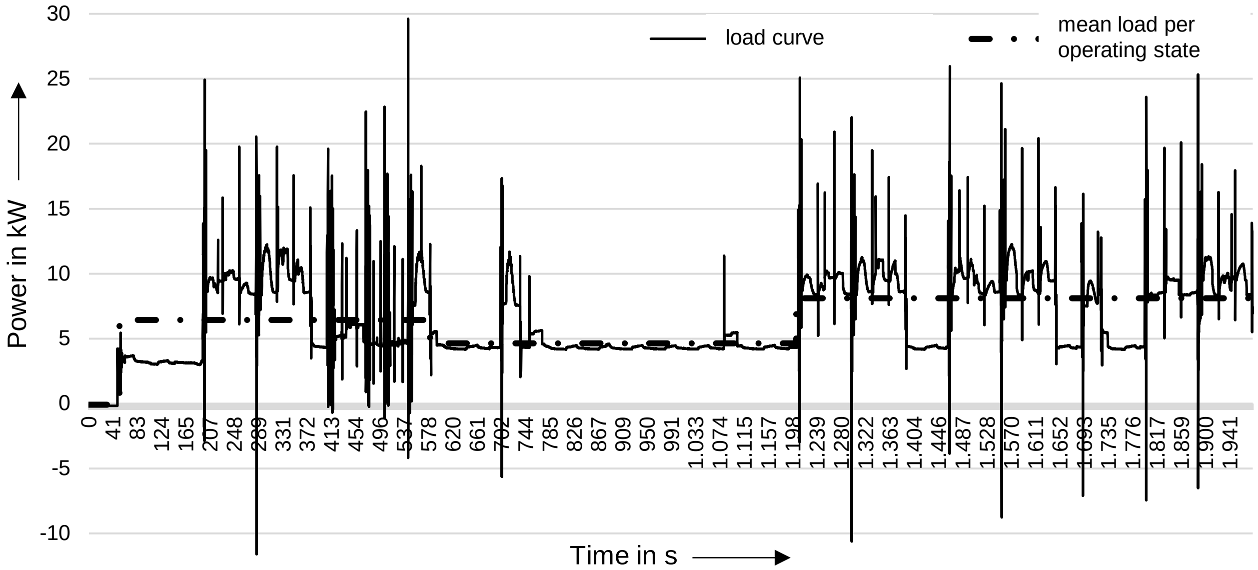

Figure 1 Necessary data to assign the energy demand.

For example [9] deals with the thematic of energy data collection. The article is considering the determination of the necessary energy data and the parallel recording of the system status as essential and emphasizes its importance. Indeed, the detailed implementation is not focused.

Consequently, the following need for action is derived:

- development of a standard definition of the necessary energy data depending on the targets of the company
- implementation of an automated detection of high-resolution production data

The subsequent chapters present a method for the systematic generation and evaluation of energy data in manufacturing.

3 APPROACH FOR A SYSTEMATIC GENERATION AND EVALUATION OF ENERGY DATA IN MANUFACTURING

To reach the aim of a method for the systematic generation and evaluation of energy data in manufacturing, the approach shown in Figure 2 is proposed.

The first step *Analysis* includes the systematic acquisition of relevant targets of regarding energy data in manufacturing companies. Furthermore, the requirements must be defined and quantified.

Within the second step *Implementation*, the determination of the appropriate sources of information as well as the available interfaces occupy a central position. Afterwards, a universally valid hardware standard has to be defined. The development and implementation of algorithms to analyze and visualize data and the realization of a measurement prototype complete the *Implementation*.

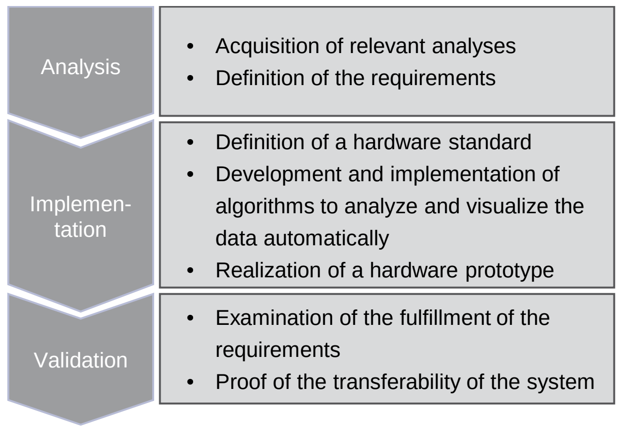

Figure 2 Approach to develop the method for a systematic generation of energy data

The third step *Validation* is to examine the fulfillment of the requirements. The proof of the transferability of the system to different production facilities and production areas concludes the method.

In the following, the three steps are explained in detail.

3.1 Methodical classification of energy data analyses

To generate and classify existing energy data analyses systematically, they are clustered on the basis of the view of a factory, in which they are established. The considered levels are shown in Figure 3.

Afterwards, for each measured target, like increasing the energy efficiency of single machine tools or production areas, the necessary

- energy data,
- operating data and
- machine data, and their

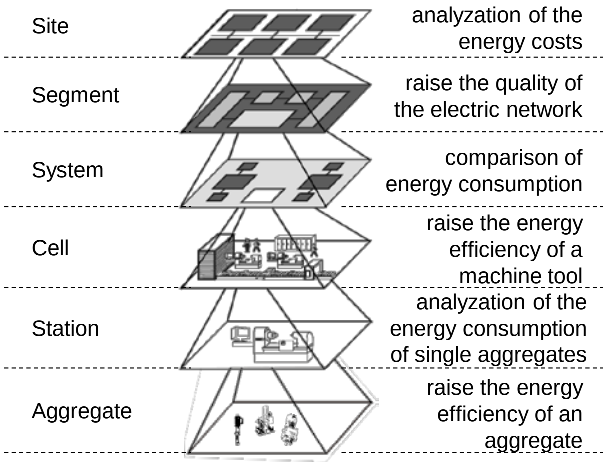

Figure 3 Views of a factory according to [10] (left) with examplary targets (right)

- measurement section,
- measurement resolution,
- recording resolution,
- technical granularity and
- measurement duration

are defined.

3.2 Development and installation of a hardware prototype

After the analysis phase the definition of a standard measurement technology and of an associated software solution have to be regarded with the four steps shown in Figure 4:

- analyzation of production facilities
- definition of a standard measuring instrument
- development and implementation of algorithms to analyze and visualize the results
- development and implementation of a visualization of the results

The first step examines the production facilities. To analyze their energy demand and production process on the basis of the necessary data, the sources of information and the individual, available machine interfaces have to be regarded. Although the different machine types and the prevalent used communication systems must be considered. Subsequently, it is possible to develop a suitable nomenclature to provide uniform semantic data for the following processing.

Concerning the measuring instrument the primary aim is the implementation of the measurement instrument to detect the required signals with the needed accuracy. Important properties of the system are the chronological synchronism of the different data and the transferability to other production facilities, for example to different machine tools or to industrial robots.

Within the development of the algorithms to analyze and visualize the data, the next step primarily consists of the implementation of algorithms to analyze the energy data automatically. Additionally, the rules for the internal data management including storage periods and the possibility of averaging the data depending on the data age must be defined.

The development and the implementation of a visualization of the results enable the use of the analyses. Therefore, it is planned to develop and realize different user interfaces with various details of the analyses depending on the current user rights. An intuitive visualization makes the analyses easy to understand.

3.3 Validation

The investigation of the requirement fulfillment concludes the method. Firstly, the system has to be tested at different manufacturing facilities regarding the functionality of the measurement, the analyses and the different user interfaces.

To finalize the validation, the scope of application of the system has to be defined clearly.

4 EVALUATION OF EXEMPLARY ENERGY DATA

In the following, an example of a possible target of manufacturing industries is shown to detail the aims of the presented method.

Machine tools are dependent upon a high quality of the intra-company electrical network. If its quality is not sufficient, there can be voltage dips, short voltage interruptions or overvoltage. As the reason for missing quality of the internal network normally is to be found in the single aggregates of a machine tool, this case represents one energy data analysis on the manufacturing level *aggregates*.

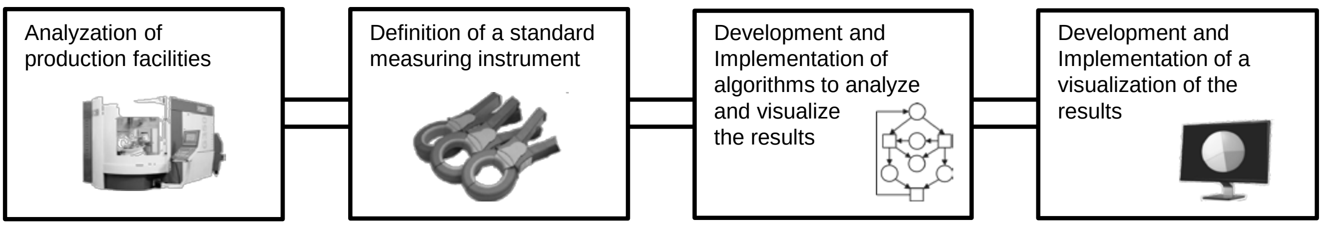

Figure 4 Four essentail steps, which have to be regared during the development of a standard hardware and an associated software solution

The quality of the electrical network is the optimization variable. To carry out the analysis, the knowledge base shown in Table 1 is necessary.

necessary data	requested quality
energy data	at level *aggregates*
operating data	operational state of the complete machine
machine data	status of the aggregates
measurement section	electrical power supply of the aggregates, operating data and machine data logging systems, SPC output etc.
measurement resolution	4 kHz
recording resolution	2 kHz
technical granularity	raw data,, e. g. amperage, voltage, line frequency etc.
measurement duration	continuously

Table 1 -Necessary data and their requested qualities

By the assignment of the single aggregates to the load curve of an active machine tool, it is possible to automatically evaluate chronological correlations between active aggregates and a voltage dip.

If an indicator cannot be measured, typical power consumptions can be assigned using pattern recognition after a few allocations of one active process to teach the algorithm. For this purpose, a pattern recognition on the basis of cross-correlation has been implemented. Figure 5 shows exemplarily the automatic detection of the beginning and the ending of several repetitions of three different manufacturing processes of a machine tool in its load curve. The algorithm is able to accept normal and unavoidable variations between the repetitions of one process. This evaluation allows the automatic comparison of active machines and aggregates with voltage dips.

On this basis, further algorithms for energy analyses will be developed.

5 CONCLUSIONS

A method to generate and analyze energy and production data systematically was introduced. For this purpose an approach in three steps was presented.

The *Analysis* encompasses the systematic acquisition of energy data and the definition and quantification of the respective requirements, which the data has to satisfy.

The *Implementation* includes the determination of the appropriate sources of information and the available interfaces. The aim is the definition of a hardware standard. After that, algorithms have to be developed and implemented to analyze and visualize the data automatically. The *Validation* reviews, whether the requirements are fulfilled and whether the system can be assigned to different production facilities.

The first automatic energy analyses have already-

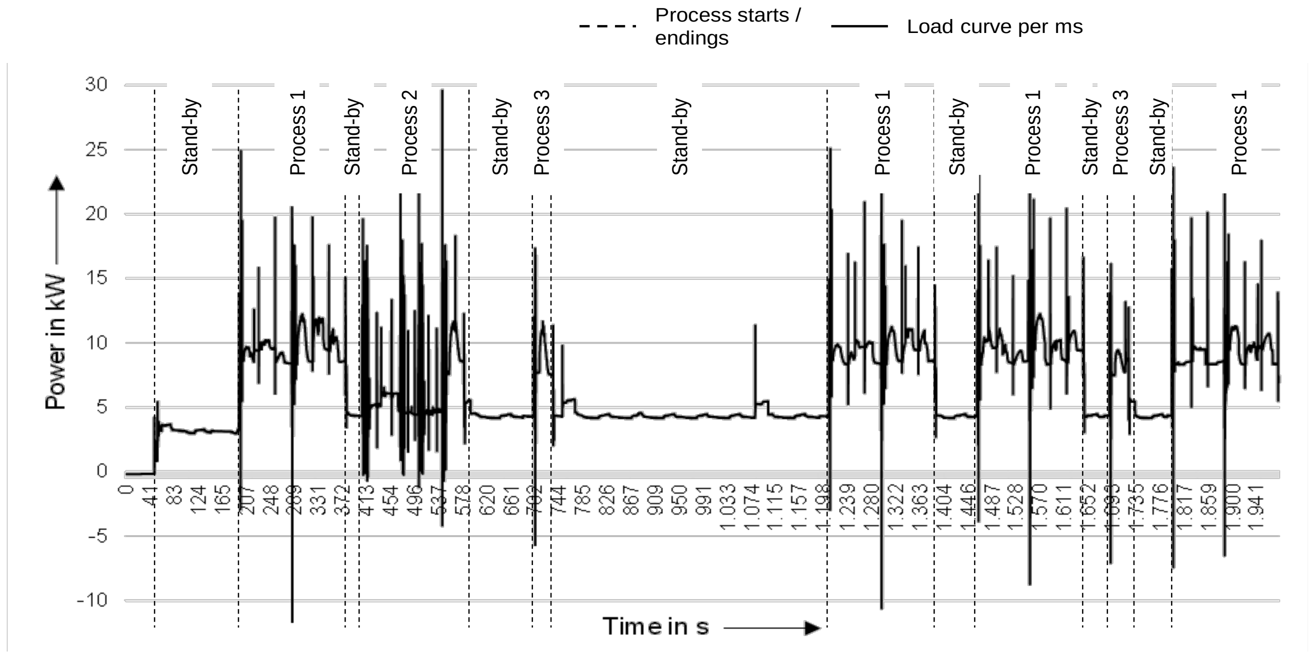

Figure 5 Automatical detection of the beginning and the ending of several repetitions of a manufacturing process of a machine tool

been performed. This took place on the basis of energy, production and machine data as well as pattern recognition.

In the future, the presented approach has to be applied to further use cases. Furthermore, the defined standard will be implemented in a hardware prototype.

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7 BIOGRAPHY

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Typology for Manufacturing Transformation towards Services Based Models and Structures – A Consistency Theory Perspective

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Abstract
There is no doubt that manufacturing industries such as the capital goods or the tool and die industry are among the most innovative from a technical point of view. However, the current competitive pressure gives reason to ask whether technology by its own will account for future competiveness. The transformation towards service based business models is proposed to differentiate from competition and gain a new position with new offerings. However, there is evidence that most of these transformations fail. As such, the manufacturing industry is facing a relevant and actual problem. The scope and complexity in such transformations is one of the main reasons for the failures. Based on our analyses, managers have difficulties in structuring the magnitude of changes in core processes, structures, culture and behaviour. In addition, there is a lack of knowledge about the key dimensions such as positioning strategy, value proposition, pricing model, organization structure and processes, internal values and performance measures and their interdependencies. The objective of this paper is to enhance the existing body of research on manufacturing transformation and industrial service management. We provide a comprehensive typology which allows the identification of internally consistent and disjoint combinations in key dimensions and variables. The typology describes theoretically based but applicable pattern for manufacturing companies to successfully transform. We enhance this pattern with a process model of transformation. Based on a comprehensive review of existing work on typologies for manufacturing transition the need for further research could be clearly identified. A research framework is developed based on the literature on industrial service management and the strategic management theory, systems theory and organizational design theory. Consistency theory is chosen to elaborate the patterns as combinations of variables. A case study approach has been chosen and results have been comprehensively validated in the German manufacturing industry.

Keywords
transformation typology; servitization; business transformation; service based business model; integrative perspective

1 INTRODUCTION

A key capability for the future competitiveness of manufacturing companies is the development and delivery of integrated solutions. The transformation towards service based business models is proposed to differentiate from competition and gain a new position with new offerings. This transformation comes along with a fundamental change of the business model, structures, processes and organizational behavior as well [1, 2]. For example, the automotive industry requires pre-production services (such as design services and research and development), production-related services (such as maintenance and IT services), after-production services (transport and distribution services) and financial services and finally other business services such as accounting or legal services.

Companies often follow the pattern described above towards service based offers expecting high gains without carefully elaborating a concept in advance and without verifying the fitting of the positioning affiliated with the new service based model in regard to the own company as well as to the respective customer [3, 4]. According to this the number of companies benefiting from this transformation is hitherto relatively small [5]. This is not due to a lack of concepts but rather on the big organizational challenges of the management regarding solution business [6].

In order to successfully transform the positioning it is necessary to elaborate the conceptual steps initiation, positioning and added value before an actual implementation. A transformation of the positioning does not solely have an impact on the position itself but has an effect concerning several relevant areas in a company as activities, behaviour as well as structures [7]. To ensure success a harmonic alignment of all relevant changes is required before repositioning [8].

2 OBJECTIVE OF DEVELOPING AN INTEGRATED TYPOLOGY

In practice there is no overview over various changes resulting from repositioning in the companies, so that a target-oriented clarification is not possible. According to a study carried out by BAIN & COMPANY more than 90 percent of those interviewees see the need for action for the management in order to successfully cope with the change into solution providers [9]. In consideration of the described actual success rate transformation is, for the companies, still related to the key challenges [3].

Not only in practice but also in science this subject is the major challenge and is considered to be insufficiently answered. Support of management is the core challenge of this transformation [10]. Models, dealing with this transformation and its effects can serve as supporting instruments in the management of companies.

The big number of potential service based models, the minor success of companies during transformation as well as the explained research results lead to the conclusion that companies need support in decision-making regarding the choice of the new company positioning as industrial service provider. Moreover the scientific consideration of this subject and the resulting core challenge associated with the support of the management indicate that there is a lack of structuring aid. This is necessary to enable a demonstration of the diverse changes in activities, structures and behaviour associated with repositioning and to support companies holistically in decision-making [11].

3 THEORETICAL FOUNDATION

In the past the enterprise was viewed and designed in parts or subsystems by taking one single view of the enterprise such as studying the organizational structure or the information architecture. A vast number of literature indicates that the main reason for strategic failures is the lack of coherence and consistency among the various components and subsystems of an enterprise [3, 11]. Consequently there is a need for an all-encompassing view of the enterprise as well as for the transition from a situation in which enterprises are evolved ad hoc fashion to a systematic engineering approach to the design of enterprises. This is given by the discipline of enterprise engineering that studies the large picture of the entire enterprise. Enterprise engineering takes a holistic perspective of the entire system and how the parts would work and interact in the system.

The transformation towards a solution provider has tremendous impact on the whole company. It is not only important to formulate the appropriate strategy including for successful differentiation, it is the integration of all relevant company activities which has to be achieved: strategy, product definition, marketing concept and the solution design process itself have to be aligned and inherently linked. In addition, all organizational structures and the company culture and employee behaviour have to be changed towards a more customer and solution orientated characteristics. E.g. there is a need for decentralised structures which concentrate the relevant competencies where they are needed near the customer.

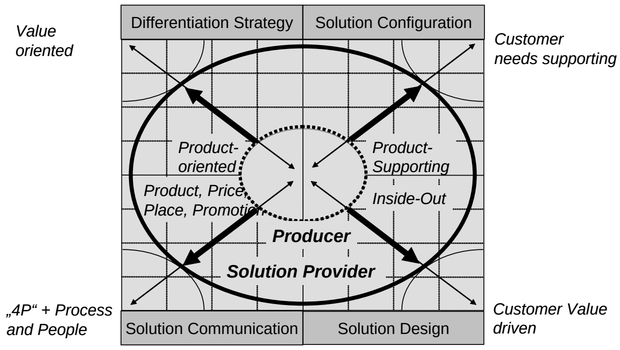

Figure 1 - Consistent integration of company activities for successful transformation (based on [10])

Figure 1 illustrates the integration needs and direction as mentioned for four important company activities: differentiation strategy, solution concept and configuration, solution marketing and communication and finally the solution design activity. The integration as illustrated in Figure 1 means that all of these activities have to be changed simultaneously towards a solution, customer needs supporting and value driven orientation. This simultaneous shift is the prerequisite to successfully implement a solution orientation within a producing company. An unbalanced change will cause tension and finally the fail of the initiative towards a solution orientated company. There are challenges to facilitate the rich interactions and cohesion between the different services or solutions and the customers. Also there are challenges to ensure flexibility and reconfigurability of services and solutions [12].

4 RESEARCH APPROACH

According to the aim of systematization, among it the framework for positioning of industrial service providers, the following three requirements have to be met in conformity with Corsten and Gössinger [13]: “Firstly authenticity is required, which means that „at least two non-empty subcategories have to exist“. Secondly it is necessary to ensure completeness, so that the objects will be captured comprehensively. Finally clarity within systematization is required; this means one item may not be classified into two or more sub-classes. According to this, sub-classes and their characteristics have to be disjoint. One the one hand aspects of description of several industrial service providers have to be compiled within this framework including all challenges of all relevant organizational fields for positioning as industrial service provider. Moreover, the description of relevant characteristics of industrial service providers, as well as its visualization requires a suitable graphic, so that the relations can be easily and clearly demonstrated. Furthermore, the diversity of realization of characteristics must be taken in consideration in an appropriate form. The results have to be modeled in accordance with the target groups, so that the target group, managers in the capital goods industry, receive practical use. According to the aim adequate positions of industrial service providers have to be identified quickly and easily by means of the framework in the application context.

5 TYPOLOGY FOR THE POSITIONING OF INDUSTRIAL SOLUTIONS PROVIDER

The following results are based on Ansorge 2014 [14]. The consistency raster shown in figure 1 has been extended by two further elements, Solution Behaviour and Solution Offering and has been integrated in a raster. Altogether the raster consists of six areas (see figure 2), according to the constituent characteristics. Between the two extremes producer (middle area) and solution provider (outside area) all further types of industrial service providers can be classified.

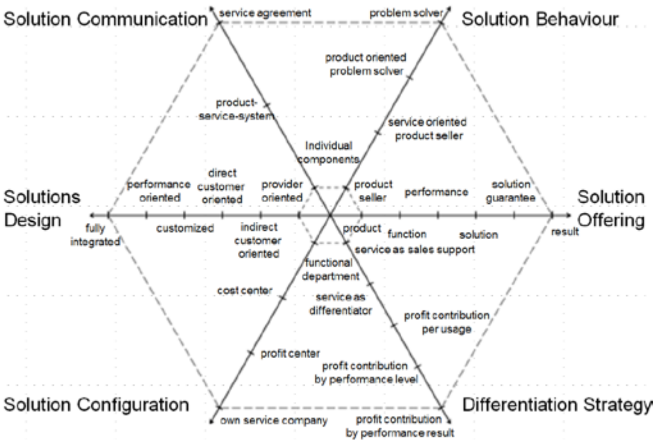

Figure 2 - Consistency raster with constituent characteristics of industrial services (based on [14])

5.1 Solution Communication

Because of the immateriality of services it is difficult to describe or even make this comprehensible for the customer. It is a challenge for the customer to recognize quality as well as benefits. Appropriate marketing is therefore more important in order to communicate the advantages of an offer to the customer. Depending on arranging the range of services offered, another consistent type of marketing is to choose. Withal marketing can be divided into individual components benefit system and service contract [15].

Solutions Design

As already demonstrated in the introduction, services are becoming more and more relevant for the success of a company. Two essential aspects are development of services and service provision. Just to develop the correct portfolio concerning services is decisive for a success [11]. The solution design focuses less on developing service in a customer-specific way, but to cover different customer demands by a wide portfolio of standardized services in a best possible way. An early integration of the customer into the development process is the key criteria for success with regard to the right interpretation of the portfolio. Only the manner of integration has to be examined more precisely. The same applies for the supply of services, whereas an integration of the customer takes place as well. On the constituting level the degree of integration into service development and service provision is used to define the characteristics [16].

5.2 Solution Configuration

The organizational structure demonstrates in which way service business is integrated into the company. The manner of organizing service business may be carried out in different ways according to the elaboration of the service. There is the possibility to integrate the service unit into the appropriate unit. Advantage of this alignment is the direct benefit of the available know-how of the staff members and the proximity to the product. Coordination can be made more easily. Such distributed service units, which are integrated as functional services in the companies, are mostly highly product-driven, so that the aims of the service and hence the aims of the service unit are rather in the field of product sale [15, 16]. Moreover, in the previous described situation several service units do exist dispersed in the enterprise. Synergy effects when solving same questions and challenges are often not used. If we consider the financial success of service units and the support for the management, than it turns out that the own company-wide service units, designed as cost or profit center, are considerably better suited. Particularly the profit center is increasingly used from successful companies in the service area [7, 15]. The establishment of an own service company is very often performed, as the risks, which may arise for the company can be separated from the company [3].

5.3 Differentiation Strategy

In order to bring the described service offer and the possibly related changes into a reasonable framework there is need for an adequate service-offer oriented competitive strategy [7]. On the basis of existing approaches can be noted that especially the part of services in the competitive strategy is interesting for a detailed description, as, among other things, the behaviour towards competition as well as towards cooperation partners and customers can be derived. Various arrangements are possible: from the mere support as sales assistant for services and differentiation possibilities up to services as relevant profit contribution. Besides, profit contribution can be realized by different variations as by customer behavior, efficiency or service result.

5.4 Solution Offering

In order to be successful as industrial service provider in the market an outside-in-reflection is required to derive a suitable service offer [7]. This means that customer needs and expectations have to be known in order to be in the corresponding position. It is important to meet the customer benefit by means of the offer. According to the customer benefit services will receive a higher importance and will become a central component in the offer to the customer. The development into an industrial service provider moves the product as a traditional service offer into the background. In fact aspects as functionality of the product or an optimal performance in the customer's process are relevant. A further variant is that the customer wishes a solution to a problem, in which the product is only one component among others. Availability for use-oriented or result-driven offers is yet another step further away from the product.

5.5 Solution Behaviour

Particularly in services the behaviour towards the customer is very important due to immateriality and is used for valuation of the service provided. An adequate and an appropriate behaviour according to the service offer is necessary. However, not only behaviour towards the customer is specified with the constituting characteristics [16]. The staff members must have understood the correct behaviour and it must be lived. Customer contact is the narrowest and most important interface to the customer. If the staff member on site supports the customer in an advisory manner, he is in the position to solve his problem in a better way and is able to offer new services to the customer. At the same time he receives feedback, which can be used to develop the service offer further on. According to different service offers the characteristics product seller, service-oriented product seller, product-oriented solution provider and problem solver have been identified to be relevant characteristics.

On the basis of the above described constituting characteristics altogether six types of industrial service providers can be identified [3]: Type I: producer – obligatory services, type II: provider of extended services, type III: extensive customer supporter, type IV: proactive solutions provider, type V: performance contractor and type VI: operator. The different types and respective characters are demonstrated in figure 3.

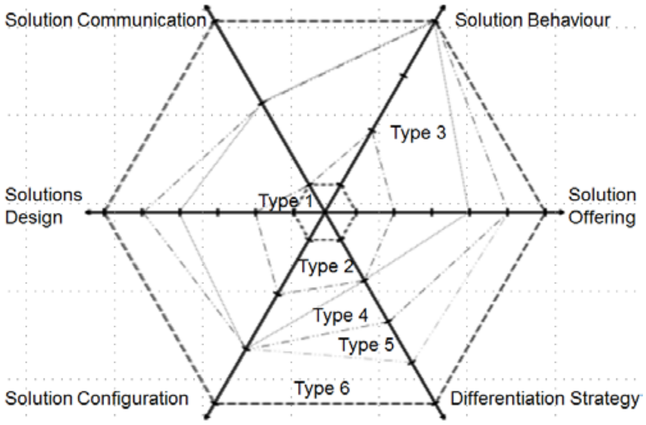

Figure 3 - Typology for Manufacturing Transformation towards Services Based Models and Structures (based on [14])

The producer (type I) focuses on activities of the product business. These include mostly less complex products; the customer is able to select a product independently and without greater consultancy. An intensive customer relation will not be developed. The relation will be limited to single transactions and marketing is designed correspondingly. Services play a subordinate role. The producer offers, partly in order to meet an obligation, obligatory services as there is maintenance, inspection or repairs. [3]. Moreover, the producer renders the services without payment. For this type services only serve as sales assistants for the products and are seen as necessary evil. By this the producer does not achieve a competitive advantage. So service is only a functional department in the company and the provider sees himself definitely as product seller.

The second typical industrial service provider is called a provider of extended services (type II). In comparison with the producer with obligatory services, services of this type take a more significant position. It does not only serve as sales assistants but serve for the provider in the sharp price-driven competition as possibility of differentiation in competition. That is why the provider of this strategic type extends his service offer. The provider completes not only his reactive after-sales-service but also adds further product-supporting and sporadically process-supporting services to his portfolio [3].

Goods are no longer focus of the provider of extensive customer support but the requirements of the customer (type III), or more precisely the performance of the machine, which shall be operated extensively by appropriate services, Services do not play any longer a subordinate role. The service offer consists of an integrated combination of goods and services. This combination can be arranged differently according to the respective customer demand. So the competitive strategy is clearly designed for differentiation. Support no longer aims at functionality only but the services offered are oriented enhanced towards processes and procedures of the customer, in which the goods are involved. Thereby direct customer integration is included in development of services and provision of services, so that services are developed according to the customer's requirements. This does not lead to individualization but rather means that the provider's portfolio better aims at the customer's requirements. The provider is rather acting as consultant in process matters and offers training courses which increase comprehension of process and procedure of the customer's staff members. This type can be called a product-oriented solutions provider. In this case of strategy option the provider supports the optimized product integration within the customer's added value.

A further enhancement would be called a proactive solution provider (type IV). He offers solutions which are individually oriented to the customer's requirements and which mainly consist of services. In this case of strategy option the provider extends his service range on differentiation and supports the customer not only in product-related and process-oriented problems; for problem-solving by considering even emotional aspects. This is mostly the first challenge in realizing the customer's requirements. Mostly the existing problem and the desired solution can only be described vaguely by the customer. He cannot supply detailed requirements or solution approaches. The provider has to elaborate a solution concept based on information received by the customer. The individual part performances in detail are not of interest for the customer as long as he is sure that the complete solution meets his requirements. In order to being able to offer such concepts of solutions, the provider needs in addition to product-related and process-oriented services customer supporting services in particular. These are aimed directly at the requirements of the customer. This leads to the fact that proactive solution providers also have to offer services, which have nothing to do with the product itself. These include e.g. a large number of analyses, economic calculation, consulting services and trainings [11, 15].

Type V (performance contractor) concentrates on the customer's need for success. With this strategy option the provider offers a comprehensive support in the use of goods during the entire service life cycle [3]. The customer then is not interested in single services or goods but expects a certain efficiency of goods within a certain time agreed on in advance. The provider needs a complex customer solution in which goods and services are closely related in order to being able to promise such a service. There is a need for a full-service over the whole period of performance warranty, so that the customer does not have to take care of the machine and the provider is in the position to provide a guarantee respectively is able to initiate early activities in order to fulfill these.

Similar to the performance contractor the operator (type 6) focuses on the customer's need for success. The operator is the only one who renders his customer not only goods and services but also produces on his own goods products for the customer. Thus he provides the customer with a production output (result), which is linked to considerable changes for the provider [3]. This type of industrial service provider combines the idea that the customer does not actually want to buy a machine in order to manufacture a product but wishes to come one step closer to his aim, the finished product. According to this services in this competitive strategy are understood as profit contribution, which is achieved in dependence on performance result. The adequate organizational structure is an independent company, as the following comments will show. The provider not only supplies the desired product, as it would perhaps be in a mere outsourcing case. In fact he integrates into the customer's added value, supports him with different services and provides additionally the product. Therefore a fully integrated service development and provision is necessary, as the detailed explanation will show. This service offer can in marketing only be promoted as a firm service contract.

6 TYPOLOGY VALIDATION

For the validation of the typology three enterprises have been chosen, which in recent years have positioned as industrial service providers although the companies had traditionally started das producers. The selection of enterprises which implemented the change so far has been taken intentionally so that the company experts can make a retroactive evaluation , have experienced the change within the own company and know about the relevant aspects and challenges.

The first case example (case 1) focuses on the technical service of packaging manufacturer. About 500 staff members of altogether more than 4950 staff members are working in the service sector worldwide. The case example is suitable for the validation of the framework in the context of large companies. The position shown in figure 4 has been achieved over the past years by various activities and projects as e.g. the extension of the service portfolio. The service offer is characterized by customer support-oriented promised benefits, which shall enable the customer to achieve a high filling quantity by optimal integration of the system at SIG in its entire process. So the customer benefit is clearly performance-oriented. For fulfilling the promised benefits the provider is in need of an integrated service offer regarding goods and services, which is characterized by an average immateriality.

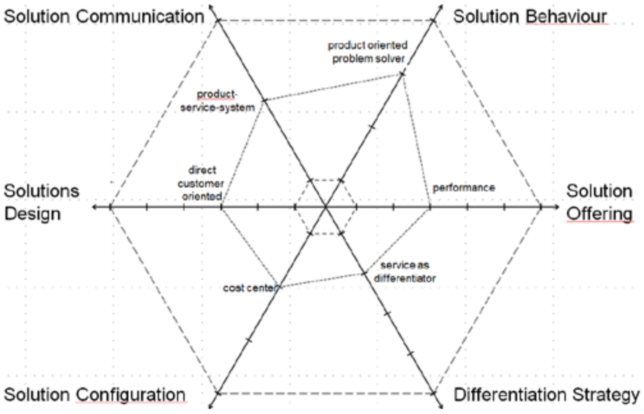

Figure 4 - Validation Case 1 (based on [14])

Within the second case example the framework was used in a medium-sized company in order to verify the applicability for small and medium-sized companies (see figure 5). The customer requires a secure availability of the system so that the initial investment is profitable as soon as possible, but also the utilization of the produces gases can be guaranteed. So the customer benefit is as part of the service offer clearly availability-oriented. This will become more important to the customer, when he uses pure gases which cause failures more quickly or lead to wear and tear on the system. He wishes to hand over the risk which is associated with this. Pro2 appropriately offers customers efficiency in the form of availability as performance promise.

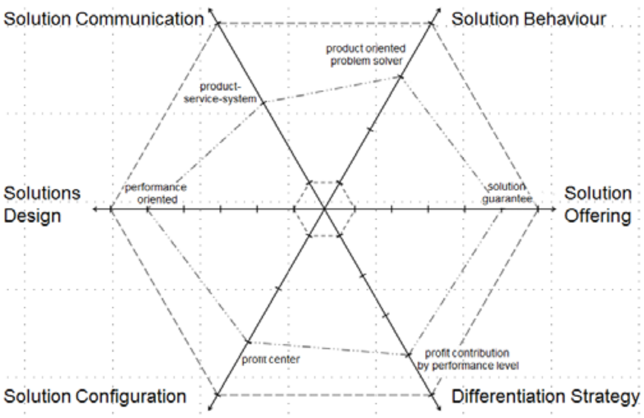

Figure 5 - Validation Case 2 (based on [14])

In order to ensure the performance level agreed on, the provider needs different services from system monitoring to preventive and reactive maintenance and which lead to a comprehensive range of services. A high immateriality is combined with this positioning, which results from the service-orientation of the service range, in this case the availability of service.

7 CONCLUSIONS

The generation of added value for the provider of service-based offers mostly remains open. The practical problem behind it is based on the management's challenge of repositioning and less on missing innovative concepts. The foundation for a successful positioning is to be laid when elaborating a consistent concept before an actual implementation of changes. In the management there is a lack of knowledge regarding the changes which are associated to and necessary for repositioning and regarding the effects on the enterprise which are distributed widely over positioning, as e.g. activities, structures and behavior.

To enhance the existing body of research on manufacturing transformation and industrial service management we developed a comprehensive typology which allows the identification of internally consistent and disjoint combinations in key dimensions and variables for manufacturer's transformation towards services based models and structures. Thereby we identified six configuration Types for the positioning of manufacturing companies respectively industrial service providers.

The developed typology offers the necessary knowledge of all concerned and relevant key areas regarding a successful positioning of services. Moreover, a consistent target position can be developed by means of typology and the different changes in the single areas can bring the parts together.

The framework illustrated in this paper supports producing companies to systematically plan the transformation from a product focused towards a service and customer knowledge centric enterprise. A simplified stepwise transformation pattern for capital goods companies is illustrated in the following Figure 6.

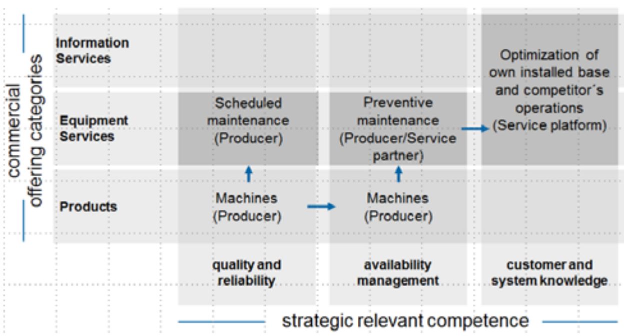

Figure 6 - Transformation pattern for capital goods companies (based on [17])

Consider an aircraft engine producer who is moving to preventive maintenance and finally expanding aircraft fleet optimization to outside its own installed base. Strategic alliances and data based platforms are developed to achieve this state. Information Services sell data and insights or manage a market that sells data. Equipment Services sell product operations and optimization services or sell the product using an as-a-service or for-performance payment model.

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9 BIOGRAPHY

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Design of a Multi Agent System for Machine Selection

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Abstract
In a machine shop effective assignment of jobs to machines is a multi-criteria decision making problem which is usually done by professionals and experienced planners. The skill of job assignment becomes handy in machine shops which are in the Small, Medium to Micro Enterprises (SMMEs) category as they work on a variety of products with limited machinery. The paper presents a machine selection system for helping decision makers when selecting machines to be scheduled. Customer order parameters which include product weight, clamping force, mould dimensions, due date and lead time are used to select moulding machines suitable to manufacture the desired parts. The criteria for machine selection was developed using Analytical Hierarchy Process (AHP) were quality, time and cost were considered as the key parameters. The available machines which meet the requirements for moulding a desired part are then made to compete for the part using an English auction. A Multi Agent System consisting of a managing agent, administrator and bidding agents was developed to conduct the auction that takes place between machine agents viewed as potential contractors representing available machines in the production line. The multi agent system is developed using Java Agent Development framework (JADE). An injection moulding plant with 11 injection moulders was used as a case study for application of the system.

Keywords
Multi Agent System, Analytical Hierarchy Process, JADE

1 INTRODUCTION

The production lines of many Small, Medium and Micro-sized Enterprises (SMMEs) in plastic manufacturing are composed of several similar injection moulding and extrusion machines. These machines have the same functionality but are different in terms of their specifications and capacity. Jobs are assigned to machines based on their capacities and their physical properties which are clamping force, dimension of tie bars, shot weight and the previous jobs characteristic e.g. material or colour.

Machine selection is determined by experienced planners making it biased and subjective to the person and also leads to loss of cost and time when the planner is absent. Since machine selection is mostly done by experienced personnel, the probability of matching a job with an appropriate machine when conducted by an inexperienced person would lead to uneconomical plan and defects. In the paper a decision support system is proposed to act as a tool to help in the job-machine assignment for an e-manufacturing system. A multi-agent based system with an auction based subcontracting approach in which bidding agents (representing machines) will bid for a job by evaluating acquired information and sending offers to the Managing agent which will select the winning bidding agent by using the Analytical Hierarchy Process (AHP).

The papers is organised as follows: section 2 discusses the background information and related research literature, section 3 discusses the proposed framework and the decision making methodology, section 4 discusses the system development with the results shown and discussed in section 5. The paper finally ends with a conclusion

2 RELATED LITERATURE

Selecting an injection moulding machine from a group of injection moulding machines is a Multi Criteria Decision Making (MCDM) problem. In the development of the problem a finite set of customer orders will be allocated on a finite set of machines [1]. However, some researchers suggested the use of parallel machine scheduling in simplifying the problem [2], [3], [4]. Usually, any machine will be selected when it matches with the clamping force, platens and mould's shot size. To improve the solution other qualities such as good for the design part and materials are required to be compatible with the existing tools under quality management [5]. Manufacturers use different criteria and priorities of criteria for the production resources available though the basis is the clamping force since it greatly affect the product [6], [7]. The selection criteria can be divided into technical factors (e.g. tonnage, pressure, open distance, tie-bar space, mould dimension, temperature, etc.) and economic factors (e.g. shot weight size) [2]. In this section we review some of the systems that have been developed to solve the injection moulding machine selection problem.

2.1 The Injection Moulding Machine Selection System

Suwannasri and Siroventnukul [8] used the fuzzy logic principle to deal with uncertainty and mechanical factors that affect quality in the development of an injection moulding selection system. The system was able to mimic the decision capabilities of humans in production planning despite limitation of time and massive information. The main setback of the systems is that the decision criteria used were not compared to another in terms of importance, thus each attribute is equally important to the next, even though in real life some factors are more important than others depending on the manufacturer being considered.

2.2 Decision system for Multi-criteria machine selection for Flexible Manufacturing Systems

To take care of the differences in importance of decision criteria Tabucanon, Batanov and Verma [9] proposed the use of Analytical Hierarchy Process (AHP) method and a rule based technique for selecting an appropriate machine for a flexible manufacturing system using a software called MASCEL. Input data was based on past information of the machine stored in a database. This system has an advantage that it allows users to add or deduct machines directly in the database via application of a Database Management System. However the system depended on all answer ratings of the users thus making the system require a high level of knowledge management and time consuming as it deals with non-standard data. MASCEL software has also been used is selecting a machine centre [10]. The results of the case studies carried out showed the use of AHP alone is not the best method to select a machine in a flexible manufacturing system as suggested by Rao [11].

2.3 Combinational Auction and Lagrangean Relaxation for Distributed Resource Scheduling

Kutanoglu and David Wu [12] used the iterative-auction approach to solve a distributed resource scheduling problem, in which a set of jobs must be performed, each consisting of a set of operations, each operation requiring a particular machine for some duration. A Multi Agent System (MAS) in which an agent is associated with each job and set of biddable items as a set of discrete machine/time slot pairs, each pair having an associated price is used. Each agent generates a single bid and the auctioneer agent examines the bid and then updates the prices in an attempt to reduce resource conflicts. The procedure stops when the auctioneer finds all the bids that are compatible. This system maps a job to machine in a one to one fashion and uses the auctions to find sets of machines/timeslots pairs to satisfy the needs of each job. The biddable items are machines/timeslots pairs; these are too many and pose a disadvantage to the system. In this paper AHP is used to reduce the candidates for auction hence reducing the biddable items.

2.4 Multi Agent Systems

A multi agent system is defined as a network of software agents that interact to solve problems that are otherwise beyond the individual capacities of each problem solver. A multi agent system is therefore one that consist a number of agents, which interact with one another. In most general case, agents will be acting on behalf of users with different goals and motivations. To successfully interact, they will require the ability to cooperate, coordinate and negotiate with each other, much as people do [13]. With the rapid growth and promise of the agent technology, a number of methodologies for developing MAS have been proposed [15]. So far no standardized design methodology has been recognized for Multi Agent Systems [16] hence a researcher intending to employ a methodology for MAS need to fully exploit all agent concepts, evaluate and analyse different available methodologies to come up with the best suitable methodology that matches the environment or system under investigation. Some of the most common methodologies include Multi-agent systems Software Engineering (MaSE) [16], Societies in Open and Distributed Agent spaces (SODA) [15], [17], Generic Architecture for information Availability (GAIA) [18], [19], Agent Unified Modeling Language (AUML) [20], and Java Agent DEvelopment framework (JADE) [21]. This research uses the JADE methodology modelled using AUML which is an extension of UML (Unified Modelling Language) developed for agents.

JADE is fully developed in Java and is based on interoperability, pay-as-you go philosophy, ease of use, uniformity and portability making it to fit the constraints on environments with limited resources and to be integrated into complex [22]. It combines a top-down and bottom-up approach to account for the overall system and applications needs. There are four fundamental phases when using JADE: planning, analysis, design, and implementation with the methodology being in an iterative nature which allows the designer to move back and forth between the analysis and design phases and the steps therein [21].

2.5 Unified Modelling Language

The requirements analysis that consists of identifying relevant data and functions that a software system would support can be easily identified using UML. The data to be handled by the system could be described in terms of entity-relationship diagrams, while the functions could be described in terms of data flows [23]. Object-oriented software development utilizes new design methodologies, and computer-aided software engineering tools such as Visio can support these methodologies [24]. UML is a language used to specify, visually model [25], and document the artefacts of an Objected-Oriented system under development. It represents the unification of a number of ideas from different methodologists. Using UML to design a system improves its maintainability and reusability. Object oriented analysis techniques offer class, use case, state chart, sequence, and other diagrammatic notations for modelling [26]. UML has been used successfully in numerous projects to model varying architectures and requirements. [27], [28], [29], [30], [31], [32].

We selected Use Case Diagrams, Sequence Diagrams and Component Diagrams for analyzing the user's requirements, the ordering of messages and documenting relationship among components. We selected Class Diagrams for representing the static structure of classes.

2.6 Analytic Hierarchy Process (AHP)

AHP is defined as a multi-criteria decision-making approach which was first introduced by Saaty [33], [34]. It uses well-defined mathematical structure of consistent matrices and their Eigen vector to generate weights on the selection criteria [35], [36], [37]. A framework for selecting machines to machine a part uploaded on an internet registry has been developed by Nyanga et al [38], [39].

Defects	Common causes	Point of trouble shooting	Ref
Short shots	Cavity not filling properly, insufficient melt volume, moisture in material, mould release agent used, high-pressure drop in mould, poor mould design	Machine, material	[5], [40]
Silver streaking	Melt temp too high, poor pressurization, water leak in mold	Mould, machine, material	[5], [40]
Sink marks	Under packing, mould malfunction, poor part design	Mould	[5]
Burn marks	Injection rate too high, lack of mould venting, clamp pressure too high	Mould, machine	[5], [40]
Flashing	Over pressurization of cavity, melt temp too high, mould malfunction	Mould, machine	[5], [40]

Table 1 - Defects in Injection Molding

2.7 Defects in Injection Molding

Table 1 shows the common types of defect and their common causes. The defect types that are affected by the selection criteria of this paper are Short Shot, Sink Mark and Burn marks.

3 METHODOLOGY

In this section a detailed empirical study based on the above stated research is presented.The system design and the algorithms employed are also described in this section.

3.1 System Requirements

The decision support tool developed will be used to award jobs to machines after an English auction between bidding agents seeking potential contractors who will be representing available machines has taken place. The User calls for an auction and inputs auction details while the Administrator agent creates an auction which is controlled and monitored by the Managing agent. The manager solicits proposal from other agents by issuing a call for proposals. The agents receiving the call for the proposals are viewed as potential contractors and are able to generate proposals to perform the tasks as propose acts. Bidding agents will participate in the auction and try to outbid one another in order to get a specific job depending on the availability of the machines. The winner of the auction/order is announced at the end of each auction.

3.2 Designing with UML notations

The decision support tool was designed using Use Case, Sequence, Class Diagrams offered by UML and the Visual Paradigm Tool.

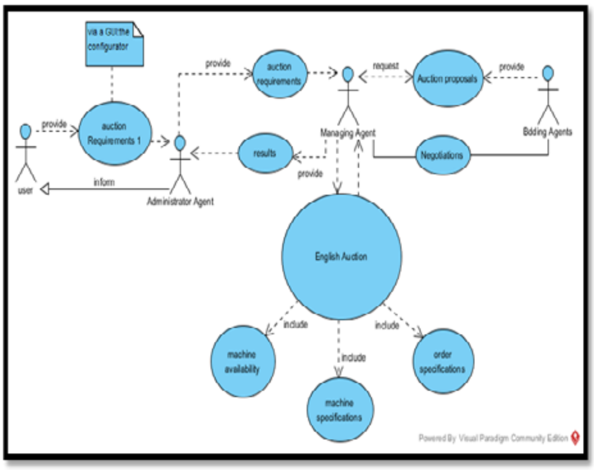


Figure 1 - Overall Use Case Diagram

3.2.1 Use Case Diagram

The Use Case Diagram is a visualization of a use-case, i.e., the interaction between the auction system that is going to be used to select the best machine for a job and the users. Figure 1 shows the Use Case Diagram for the overall actions that the User (qualified production personnel) can perform in an auction as the manager and the bidding agents are interacting.

3.2.2 Class diagram

A class diagram describes the types of objects that exist in the system and the static relationship among internal classes of the system. Class diagrams are important entities in object oriented-analysis and design as they show attributes and the operations of a class and the way the objects are connected. Figure 2 shows the class diagram for the auction system. An abstract class (e.g., user class) abstracts common characteristics (attribute, operations, machine capabilities and specifications) about an actor.

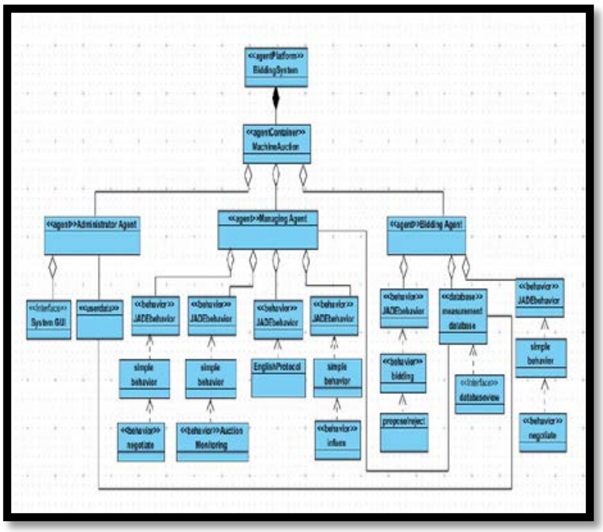


Figure 2 - Overall Class Diagram

3.2.3 Sequence Diagram.

The role of the Sequence Diagram is to display the overall flow of control in an object-oriented program. Typically, it captures the behaviour of a use-case. Figure 3 shows the Sequence Diagram for the events that occur during the auction and the role and decisions that are to be made by each agent.

3.2.4 Machine selection

A machine selection framework with three factors which are the quality, cost and time based on the framework developed by Nyanga et al [38], [39] was used in selecting the machines that will participate in

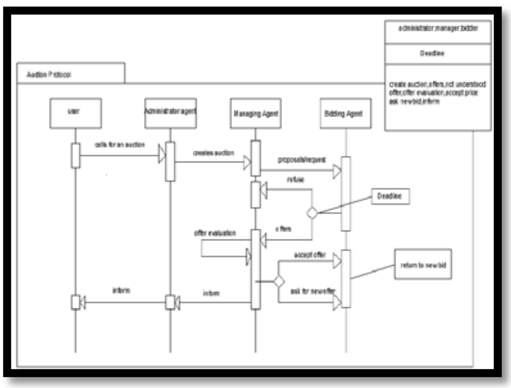


Figure 3 - Sequence Diagram

the auction. Figure 4 shows the three main factors and their sub criteria. Analytic Hierarchy Process (AHP) was used to give weights to the machinery factors that were considered when the auctioning system is taking place.

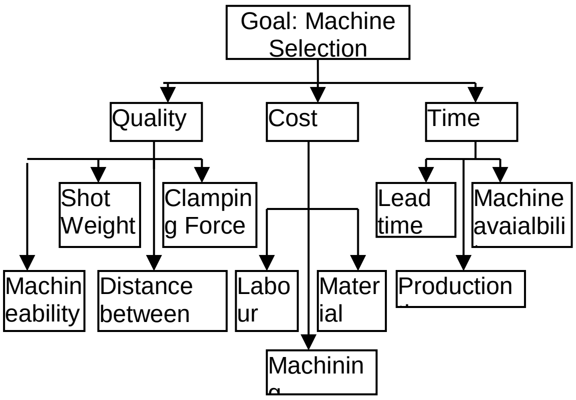


Figure 4: Machine Selection Factors

The pairwise comparisons were developed by considering the relationship between the general criteria i.e. quality, cost and time. A half matrix where the relationships of the criteria on the rows are compared to the criteria on the column is developed. To develop the matrix questions like: “How important is quality of the product as compared to the cost of production?” The answers

	QUALITY	**COST**	**TIME**
QUALITY	1	6	8
COST	$\frac{1}{6}$	1	$\frac{1}{5}$
TIME	$\frac{1}{8}$	5	1

Table 2 - Main Criteria Ranking

to the question are given in the scale 1-9. The values for the pair wise comparisons were obtained through interviews of work workers (production manager, sales manager and clerk). Table 2 shows the main criteria ranking of the factors that are considered in the plastic manufacturing company where the information was taken from.

Three iterations were performed on the square matrix to find the Eigen vectors for the criteria. The results of the final iteration are shown in Table 3.

	Quality	**Cost**	**Time**	**Total**	
Quality	6142.7	69337	26118	101597	0.7554
Cost	544.08	6142.7	2311.1	8998	0.0669
Time	1444.3	16323	61427	23910	0.1777
Total				134505	1.000

Table 3 - First level criteria Eigen vectors

Thus the Eigen vector values for the first level are as followes: Quality =0.7554, Cost=0.0669 and Time=0.1777.

Each machine attribute will be used by multi-agents in the bidding process. The contribution is given by the following

$$f(x) = \frac{machine\ attribute}{required\ part\ attribute} \quad (1)$$

The machine attribute is multiplied by the Eigen value of the main factor then by the Eigen value of the sub-criteria to get the weight of each attribute.

4 SYSTEM IMPLEMENTATION AND RESULTS

This section sets out the artefacts of our study as well as the implementation which followed the system analysis and design. The details of system configuration and analysis of the result of the empirical study are presented.

Machine name	Shot weight (g)	Clamping force(ton)	Distance between tie bar x(mm)	Distance between tie bar y(mm)
INJ1	28	30	260	260
INJ2	28	30	260	260
INJ3	45	50	300	300
INJ4	45	50	300	300
INJ5	45	50	300	300
INJ6	56	50	310	300
IINJ7	56	50	310	310
MC1	60	60	310	300
MC2	80	70	330	350
MC3	100	85	350	380
MC4	100	85	350	380

Table 4 - Machine Specification

4.1 Data Collection

Eleven machines with the specifications shown in Table 4 were selected to develop the proposed system. Information on the machines was obtained through interviews and data collected from the production planner of the plastic manufacturing company

4.2 Graphical User Interface Design

The user interface for the MAS program was developed that eliminated the need to create scripts or to type commands at the command line so as to accomplish a specific task. This enables the interaction of the program with the user. The GUI is shown in Figure 5: Graphical User Interface Design and serves the purpose of adding the values of the main parameters for job-machine allocation. The user page shows six main parameters that require the user to enter details, and these are the product weight, clamping force, mould dimensions the due date and the lead time. The Administrator agent will terminate if any on the values are not entered upon start up. The user will also able to view the orders in the database.

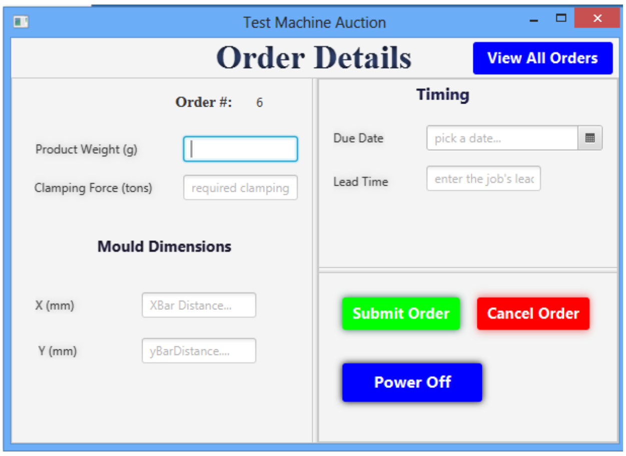


Figure 5 - Graphical User Interface Design

4.3 Agent Support System

The MySQL database storesr all the computed data up to the last decision is made. The data store is only temporary, as data can be removed from the structure. MySQL runs under the XAMPP Platform.

4.4 MAS Decision Support System Processing Procedure

Figure 6: System Flow Chart shows the system flow chart for the job auction. The Managing agent searches for available bidding agents who are able to process the job. The available machines reply to the managing agent calls by sending status messages. The auction starts, and the available bidding agents send bids to the managing agent. The auction has four main rounds. Each round lasts for 10 seconds. The manager calls for proposals and the available bidding agents respond by sending bids to the managing agent and the managing agent acknowledges the bids by sending Bid Received Message to the bidding agents thus the start of the auction. As the auction progresses the English protocol is used to get the winner of the auction. The manager then announces the winner to the bidding agents. The winning agent acknowledges that it can perform the given order by sending a message of acceptance. The loosing agents acknowledge to the managing agent that they have received the winning agent message and the auction ends. After the auction, the managing agent asks the administrator agent if there are more orders in the database and then it given permission to go and look for more orders in the database and then conduct another auction until there are no orders left with a status of zero.For each auction, the results are stored in MySQL database and the user can access the information to see the different states on jobs that have been allocated to different machines.

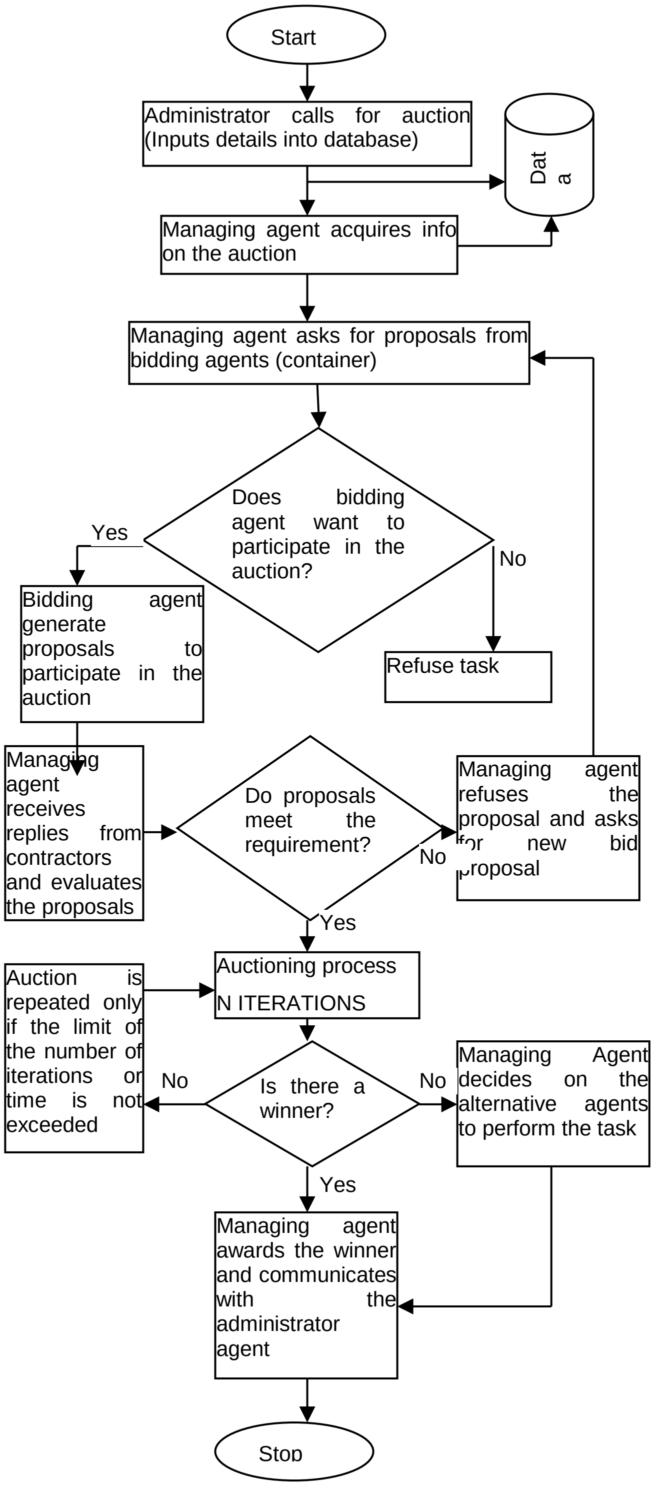


Figure 6 - System Flow Chart

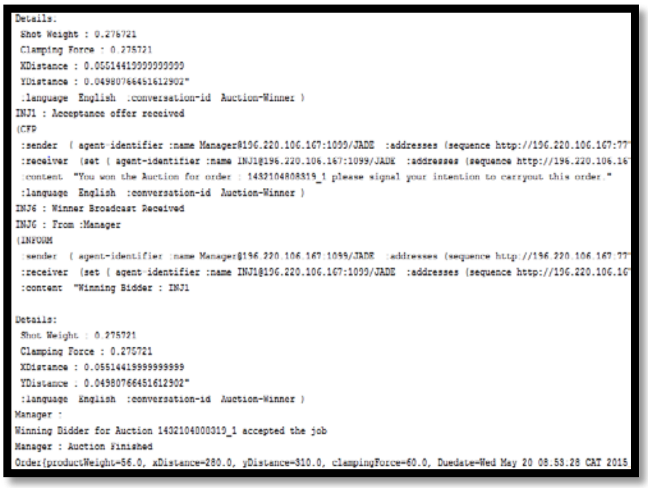
4.5 Agent Communication

A Sniffer agent shown in Figure 7 was used to view agent messages between the Managing agent and the Bidding agents as the auction was in progress. Messages were intercepted to observe how the agent society was exchanging communicative or systematic messages thus debagging the MAS.

Figure 7 - Sniffer Agent Interactions

4.6 Results and Discussion

When the auction is complete the manager agent announces the winner to the bidding agents. The winning agent receives a message from the manager that reads “you have won the auction for order number #”. The winning agent then acknowledges that it can perform the given order by sending a message of acceptance. The loosing agents acknowledge to the managing agent that they have received the winning agent and the auction ends. Figure 8 shows the details in JADE as the managing agent announces the winner as the auction ends. Though the system could select a machine the suitability of the machine needed to be tested. The level of defects discussed in Section 2.7 were used to compare the outcome of the system to that of a human expert whiuch is the current system used at company. The system was tested based on daily production reports which were collected in mid-July to mid-August 2015. Due to limited resourses only one machine was used for evaluating the ststem. In order to to compare how the proposed



```
Details:
 Shot Weight : 0.276721
 Clamping Force : 0.275721
 XDistance : 0.0551441999999999
 YDistance : 0.0498076645161290?"
 :language  English  :conversation-id  Auction-Winner )
INJ1 : Acceptance offer received
(CFP
 :sender  ( agent-identifier :name Manager@196.220.106.167:1099/JADE  :addresses (sequence http://196.220.106.167:77
 :receiver  (set ( agent-identifier :name INJ1@196.220.106.167:1099/JADE  :addresses (sequence http://196.220.106.16
 :content  "You won the Auction for order : 1432104808319_1 please signal your intention to carryout this order."
 :language  English  :conversation-id  Auction-Winner )
INJ6 : Winner Broadcast Received
INJ6 : From :Manager
(INFORM
 :sender  ( agent-identifier :name Manager@196.220.106.167:1099/JADE  :addresses (sequence http://196.220.106.167:77
 :receiver  (set ( agent-identifier :name INJ1@196.220.106.167:1099/JADE  :addresses (sequence http://196.220.106.16
 :content  "Winning Bidder : INJ1

Details:
 Shot Weight : 0.275721
 Clamping Force : 0.275721
 XDistance : 0.0551441999999999
 YDistance : 0.0498076645161290?"
 :language  English  :conversation-id  Auction-Winner )
Manager :
Winning Bidder for Auction 1432104808319_1 accepted the job
Manager : Auction Finished
Order{productWeight=56.0, xDistance=280.0, yDistance=310.0, clampingForce=60.0, Duedate=Wed May 20 08:53:28 CAT 2015
```

Figure 8 - Auction end output on JADE

system improved the defects only the top five defect types that were produced on the examined machine as they accounted for 75% of all defects.

From Table 5 Short Shot, Sink Mark and Flashing were reduced to 22.0% ,5.0% and 30% respectively. These results show that if the proposed system was used, there can be a reduction costs of reprocessing, waste treatment, and inventory. Short Shot and Sink Mark are affected by selecting the machines that have maximum clamping force lower than required force for products and low shot size. There is unconformity of mold closing, low density of melted material and leads to Sink Mark

Faults	**Current System**	**Proposed System**	**Reducing percentage (%)**
Short shots	400	312	22
Sink Marks	200	190	5
Burn marks	100	100	0
Flashing	450	315	30

Table 5 - Defective volume recorded from the test machine

5 CONCLUSION

This research was carried out in an aim to develop a machine subcontracting system for plastic injection moulding machines as a tool to help users in making decisions when it comes toin the job-machine assignment. The effective machine-job assignment of injection moulding machines is crucial because it directly affects the quality of the product, performance and the life time of the machines. This research proposed a decision support system based on a multi agent based system to select the most suitable machine for a given order. The five criteria of clamping force, distances between tie bars, shot weight, time and cost were obtained from a plastic manufacturer's case study in order to construct the multi agent system using JADE. Data of job orders and defectives were recorded within July to August 2015 and were categorized by defect types. The results showed that the system was able to reduce the defects of Short Shot and Sink Mark by 10% and 5% respectively. Moreover, Flashing was decreased by 30%.

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How to Train Employees, Identify Task-Relevant Human Factors, and Improve Software Systems with Business Simulation Games

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Abstract

In today's globalized world, cost pressure, the demand for higher production efficiency, and growing product diversity lead to increasing complexity of manufacturing and business processes. Insufficiently understood human and social factors further increase this complexity. Game-based learning environments and business simulation games can reduce this complexity by identifying and understanding the contributing human factor. Business simulation games can be used (1) to identify and quantify human as well as social factors influencing the effectivity and efficiency, (2) to assess the aptitude of prospective employees and identify suitable training interventions, (3) to improve management and production software, and (4) to present effective, efficient, and entertaining training environments. By allowing employees to investigate cause-and-effect relationships of simulated manufacturing and business environments, they can test and understand the consequences of their actions in safe environments. In this paper, we report a practical case of a business simulation game for conveying quality management strategies. The development of the game is presented along the definition of learning objectives, the underlying System Dynamics model, and the design of the user interface. The evaluation of the game reveals that human factors relate to the simulation's metrics. Finally, we give guidelines to design and develop game-based simulation and training environments.

Keywords

Game-Based Learning, Simulation-Based Learning, Serious Games, Vocational Training, Human Factors, Usability, Usability in Production Engineering

1 INTRODUCTION

Today's manufacturing companies are facing profound changes due to increasing globalization, supply chains growing in size and complexity, and innovations in industrial Internet. An increasing number of product variants, growing demands on product quality, and shorter lead times pose tremendous challenges for employees managing the flow of information and materials across supply chains of companies. Companies that successfully manage the increasing complexity, reduce the variance of production processes, and enable employees to successfully handle variance will gain the necessary competitive advantages to sustain at tomorrow's markets.

Diverse technical approaches target the increase of overall productivity and to make systems more resilient against variances [1]. Still, the human factors' perspective is often neglected despite its evident importance: Studies show that overall productivity can be increased if ergonomics and human factors are adequately considered [2,3].

Preparing employees to handle complexity, variance, and uncertainty is also delicate. Often, courses and learning modules in schools, universities, job training, or advanced trainings focus on teaching single bits of information. However, parts of the complexity of today's world stem from its interconnectedness and reciprocal interference. We argue that this interconnectedness is difficult to communicate and that adequate simulation models embedded in game environments allow employees to gain a deeper and connected understanding of the complexity of today's world. This networked thinking will empower employees to handle the increasing complexity successfully [4].

The structure of this article is as follows: Section 2 defines the terms *game-based learning* and *serious games* and gives examples from business and production engineering. Section 3 contours the benefits of game-based learning environments. Section 4 demonstrates the development of a game, the underlying simulation model, and the development of the benchmark function that was used to investigate our hypotheses. Next, Section 5 depicts studies that investigated and (mostly) confirmed the hypotheses of the versatility of these games. The article concludes with Section 6 and a summary and discussion of game-based learning environments to strengthen the competitiveness of companies.

2 BACKGROUND AND EXAMPLES

A literature review on the terms "*serious games*" and "*game-based learning*" yielded over 2 million results each. Even for the domain of production engineering, the examples for game-based learning are ubiquitous. Therefore, we start with a formal definition of serious games and implications for production engineering (Section 2.1), alongside the most prominent examples of serious games for production engineering (Section 2.2). A comprehensive overview of business simulation games is given in [5].

2.1 Background

Serious games are typically used to mediate knowledge or behavior change for educational purposes. They are entertaining but not intended primarily for amusement [6]. Furthermore, Michael and Chen state that game models are simplified abstractions of a problem and not necessarily complete and precise [7]. Prensky even argues that serious games will be the most successful method for the Millennials' and following generations' education as they grew up fully surrounded by technology and often find conventional media and earlier didactical approaches boring and cumbersome [8].

As shown above, the necessary skills to manage the complexity of today's world is beyond declarative knowledge; rather it includes procedural knowledge and the understanding and internalization of cause-and-effect relationships. Bogost highlights that the procedural rhetoric of serious games persuades to increased interaction with a topic which yields a deeper understanding of the modeled processes [9].

2.2 Examples

First, Forrester's Beer Distribution Game (BDG) illustrates the effect of variance along a supply chain by placing several players along a supply chain for an alcoholic beverage [10]. Ordering information is passed upstream (from a retailer to a factory), whilst goods are delivered downstream, each with a short time delay. The game serves two learning objectives: First, the players are sensitized to the "bullwhip effect", i.e., orders along supply chains are prone to escalation. Second, sharing information reduces this escalation.

Goldratt's game is a second prominent example and demonstrates the difficulties that arise from variances in delivery reliability or product quality [11]. The game is similar to the BDG, however, depending on random factors, only a subset of an order is delivered. This introduces significant variance along the supply chain and makes meeting the market's demands difficult.

Both games are typical contents in business, engineering, and management classes, because they raise the awareness for critical aspects of supply chain management. Players need to find a trade-off between different components of the system and have to understand that optimizing for a single aspect of the environment is insufficient and detrimental. Hence, successful players develop an understanding of the interconnected system (and its interdependent factors), infer the current state of the system from a limited number of variables, and choose the optimal or an adequate of many possible actions. The proficiency of players can then be evaluated by investigating the players' actions or their overall performance.

3 THE VERSATILE BENEFITS OF GAME-BASED LEARNING ENVIRONMENTS FOR MANUFACTURING AND BUSINESS

This section postulates that game-based learning environments in manufacturing and business offer several short- and long-term benefits for academia and industry. The following arguments militate in favor of this posit.

First, by studying workers' behaviors and their decisions, the game environments can **measure individual workers' skills and their awareness** for effective and efficient handling of specific situations in production environments. Hence, they are suitable recruitment tests and can identify training demands, if workers lack the respective skills or awareness.

Second, the game environment can serve as **training environment** in order to sensitize future employees for the challenges of production processes and to gain experience in handling specific situations that occur during these processes. Difficult situations can be explored and trained without putting the company at risk.

Third, that game-based learning environments are a versatile method to understand the underlying human factors. They can **identify cognitive, social, or emotional aptitudes** that are beneficial or crucial for handling complex situations.

Forth, we argue that game-based learning environments can help **advance business software**, as they can be used to empirically study how information presentation, amount, and complexity influence the decision quality of employees. Also, they can be a benchmark with high ecological validity to evaluate changes and new features in enterprise software.

The overall utility of the game environment in this context can be demonstrated by investigating the relationship between user factors (e.g., age, expertise, cognitive abilities), interface factors (e.g., font sizes, screen layouts, visibility of key performance indicators), and the complexity of the simulated environment (e.g., seasonal movements vs. predictable linear growth) on metrics from within simulated environment.

4 DEVELOPING GAME-BASED LEARNING ENVIRONMENTS

The development of a game-based learning environment builds on three fundamental constituents: First, a simulation model that provides a suitable abstraction of the world, and in our case, an abstraction of a supply chain, a company, or a production process. Second, a user interface that communicates the state or part of the state of the simulation model to the user and allows the user to interact purposefully with the simulation model. Third, one or multiple functions from within the simulation model that serve as a benchmark to evaluate the performance of the players.

This paper illustrates the development steps using a game-based learning environment for mediating expertise in material disposition and quality management for manufacturing companies. Although this example and the simulation model are quite specific, the general development procedure can easily be adapted to other learning objectives or application contexts.

4.1 Development of a simulation model

This section exemplifies the development of an abstract simulation model for a game-based learning environment. It is based on the Quality Intelligence Game (QIG); a detailed presentation of this model, its motivation, and the underlying assumptions are presented in [12]. The development of a model is based on three interleaved steps. Frist, the learning or research objectives need to be defined. Second, a model of the necessary cause-and-effect relationships needs to be specified. Third, based on the identified relationships, simulation functions are specified for each component.

As a first step, the learning objectives need to be identified. For this game, two objectives were selected that have to be balanced by the players: As in the BDG (see above), the first goal is to maintain sufficient stocks of a product and to always fulfill the orders of a simulated customer. The second goal incorporates product quality into the BDG and high product quality ought to be achieved by investing in the incoming goods inspection and in the internal quality assurance. The objectives are to increase the awareness for the importance of quality management and to increase the skill of the players to apply quality management strategies.

The second step is the identification and definition of the components and cause-and-effects relationships between the components in the models. We suggest using a System Dynamics model [10] as a basis for this work. In our example, the model consists of the components for 3-tiers of a supply chain with the external supplier (S), the player as the manufacturing company (M), and the customer (C). Other components that relate to the production process are also part of the model. For example, in our model the supplier's and internal production qualities can change over time. Further components are the number of intact and broken parts delivered from the supplier (both depend on the supplier's production quality), the number of intact or broken parts in stock (depending on the deliveries), the number of goods complained about by the customer (depending on the stock and the internal production quality), and the net profit achieved (depending on complaints by the customer, investments for quality inspections, stock keeping, and stock-out-penalties). Figure 1 shows an overview of this model.

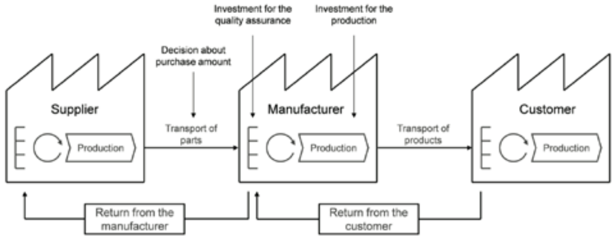

Figure 1 - Simplified model of the Quality Intelligence Game (QIG)

For reasons of simplicity and controllability, the current model is designed for a single player that controls the material disposition and quality management of the manufacturing company (M) whereas supplier (S) and customer (C) are simulated through an artificial intelligence.

This step is the most difficult and most crucial part of developing a game-based learning and simulation environment: On one side, the model needs to be sufficiently complex to capture all previously defined learning and research objectives. On the other side, it should not be too complex, as the following implementation steps will be more difficult and the users will have more difficulties to interact and understand the model [13].

In the third step, the simulation of the model's components is defined as functions of the previously identified cause-and-effect relationships. For example, the stock level S at a given time t is based on the previous stock level, the goods ordered from the supplier O, and the deliveries D to the customer:

$$S(t) = S(t-1) + O(t-1) – D(t)$$

The net profit P(t) at a given time t is based on the current stock level S(t) and the per part stock-keeping costs $cost_{Stock}$, the investments in the incoming goods inspection I_{igi} and the internal production quality I_{ipq}, the costs for the complained parts, and the revenue R(t) for the delivered parts:

$$P(t) = R(t) – c_{Stock} \times S(t) – I_{igi}(t) – I_{ipq}(t) – C(t-1)$$

A deeper presentation of the model is given in [12]. Depending on the modeled process or company and the addressed learning and research objectives, the parameterization of the functions can weight specific factors (e.g., out-of-stock penalties) as more important than others by assigning different penalties and rewards to them. We argue that the parameterization should relate to the objectives and the later use context of the game.

After the full specification of the simulation model, it can be implemented and tested as a low-fidelity prototype (e.g., in a spreadsheet application) or as functional application in a programming language.

4.2 Development of a user interface

In order to let players interact with the simulation, a user interface needs to be designed and implemented. Again, this step depends on the learning objective defined at the beginning.

First, developers need to identify which of the variables from the simulation model should be visible to the user and which should be concealed. The latter is important, as often parts of the model are intentionally hidden from the user. For example, the internal production quality in QIG is designedly invisible to the user, as she or he has to infer changes to this metric from other variables. Obviously, not all variables need to be visible all the time and the user may be given the option to request additional information on specific variables (e.g., the temporal trend of a variable or a decomposition of aggregated values). Second, the designers must also reflect how to represent each variable as an indicator in the user interface. For example, variables can be represented numerically ("102 parts"), using analog scales, as absolute or relative values ("production up 10%"), or using traffic lights ("stock level red").

For this design process, it is advised that developers consider relevant guidelines during the design and development of the user interface [14,15] and consider the learning and research objectives. For example, the user interface development for the QIG started as paper prototype: By this, the necessary indicators and controls for interacting with the model could easily be redesigned and evaluated until a suitable spatial layout was found.

Third, the simulation model and the user interface must be implemented as computer applications. Although some simpler games can be played as board games (e.g., Beer Distribution Game), we argue for using computer applications, as they can easily handle sophisticated simulation models, can log each simulation step, and log every user interaction for later analysis. For the QIG, the game was realized as a web application using Java EE and the PrimeFaces framework. Following the Model View Controller pattern (MVC) [16], the user interface (V) is distinctly separated from the simulation model (M) and one component can be changed without affecting the other.

4.3 Choosing meaningful benchmarks

Even an abstraction of a company offers various metrics to investigate. As the main objective of a manufacturing company (or likewise of a division or cross-company supply chains) is the realization of profits, the net profit P(t) seems to be the most suitable generic metric. It includes costs for investments, stock keeping, out-of-stock penalties, and penalties for complaints due to low product quality. Obviously, the inspection of other variables from the simulation may also provide valuable insights, depending on the learning objective or specific research question. For example, lead times, achieved customer satisfaction, or total product quality may also be worth studying. These metrics are already part of the simulation model (s. Section 4.1) and their relationship with the users (abilities), the user interface (visual and cognitive ergonomics), or simulation factors (complexity of the environment) can be investigated.

5 EXAMPLE: THE CASE OF A QUALITY MANAGEMENT GAME

This section outlines the empirical studies carried out to show game-based learning in the four previously mentioned application fields. Although the findings relate to the presented QIG and an implementation of the Beer Distribution Game we did earlier, the general methodology is transferable to other game and simulation environments.

5.1 Training environment

Our studies show that the games are suitable training environments as interacting with them had a significant influence on three key variables [17,18]: First, in both games, the users showed an increase in net company profits between multiple rounds of the game. Hence, players learned to perform their tasks and understood how to react to the challenges in the game. Second, in the quality management game, the average product quality also increased. Hence, the central learning objective was achieved. Third, summative questionnaires revealed that players had a higher awareness for the mediated learning objectives, i.e., the awareness for the bullwhip effect and quality management increased.

5.2 Identification of training potentials

In line with the previous section, the investigated metrics (achieved net profit, product quality, and awareness) can likewise be used as benchmarks to identify the suitability of a potential employee for a specific task or to identify training potentials.

Similar to an assessment center or as a part of one, candidates might be screened for their domain skills using an adequately designed simulation. Selection criteria might be how fast candidates get acquainted with the system (i.e., learning curve) or the performance achieved on average. However, the reliability and external validity of this approach is currently unexplored and further studies need to investigate the predictive power of achieved game performance on later job performance. Likewise, this approach may also identify training potentials. If the performance achieved is below a certain threshold or erroneous reactions are performed in specific situations, the system might suggest adequate training interventions.

5.3 Identification of human factors on performance

Regarding the identification of underlying human factors relating with performance in the business simulation games the results are promising, though they leave room for further research endeavors [17–

19]. No strong relationship between game performance and a set of investigated personality factors (different between the studies) was discovered yet. Still, some findings were coherent across all studies: The players' performances in later rounds of the game were strongly correlated with the performances from earlier rounds. Consequentially, some players are better in the game and others are not, which is a strong indicator for the existence of yet undetected personality factors that will eventually explain performance.

5.4 Evaluation of user interfaces

Multiple experiments investigated and quantified the influence of information presentation and usability on the players' performance.

An experiment in the context of the game revealed that usability and decision complexity interact in regard to performance, meaning that employees have additional and often avoidable difficulties to make correct decisions in complex situations if the data presentation is inadequate [20].

In a second study, a holistic refinement of the game's user interface was compared with the original interface [18]. The revised interface featured a process-oriented layout of screen elements and controls and integrated several key-performance indicators on important variables of the game (e.g., stock-level, product quality, refusals). To investigate the influence of this refinement, a randomized trial with both interfaces as between-subject variable and all other aspects, such as the game's complexity, held constant was carried out. The results show that reorganizing the interface towards a process-oriented presentation and the integration of key-performance indicators support players to achieve higher overall profits and higher product quality.

Future studies will break down the several changes to the interface and individually quantify the efficacy of data presentation, interface layout, and the presence of key-performance indicators. The long-term objective is to develop visualizations of relevant company metrics that adapt to the current user and context to support employees in difficult situations. This approach offers the opportunity to test and evolve user interfaces and user interface guidelines for engineering enterprise software under more realistic conditions than in controlled laboratory studies.

6 DISCUSSION

Embedding simulation models of supply chains, companies, or production processes in games enables players to interact with several aspects of the respective system simultaneously. They can develop, test, and evaluate hypotheses about the relationships of the environment, and deduce a holistic understanding of complex and heavily interconnected systems. Hence, these environments can and should be used to prepare employees for their job and to enable them for networked thinking necessary to sustain in today's world. Using games is especially useful for motivation and to address Millenials and later generations. These generations grew up with current entertainment technologies and are reluctant to use conventional media and prior didactical approaches in their education. We showed that using game-based learning environments increased the awareness for the selected learning objectives and increased the skill of the players to handle the required tasks.

Companies further profit from this approach as they can easily and cost-effectively identify training potentials for their employees or identify personnel with high suitability for the task. At the same time, the game-based simulation and learning environments can then be used as a fun, entertaining, and cost-efficient training intervention.

We demonstrated that these games could also be used to evaluate changes to the user interfaces or work environments. Software development companies of Enterprise Resource Planning Systems can therefore use game-based simulation environments to identify key interface aspects contributing to increased effectivity, efficiency, and user satisfaction [21]. Interface developments can be benchmarked along the models' relevant cost functions and our studies found evidence for the positive influence of interface refinements and the integration of key performance indicators on profit.

Although we identified a strong correlation between a player's performances across the levels, none of our thus far tested factors related well with the overall game performance. The conclusion of this is two-fold: First, the correlation hints at the existence of one ore more general human traits that explain performance. Second, this or these factors still remain unidentified and require further investigation.

Concluding, game-based learning and simulation environments for manufacturing and business are a viable method to increase the competitiveness of manufacturing companies.

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A Good idea Is Not Enough: Understanding the Challenges of Entrepreneurship Communication.

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Abstract

This paper addresses a less-investigated issue of innovations: entrepreneurship communication. Business and marketing studies demonstrate that new product development processes do not succeed on good technical invention alone. To succeed, the invention must be appropriately communicated to a market and iterated through dialogue with potential stakeholders.

We explore this issue by examining communication-related challenges, abilities and barriers from the perspectives of innovators trying to enter an unfamiliar, foreign market. Specifically, we summarize results of a set of studies conducted in the Gyeonggi Innovation Program (GIP), an entrepreneurship program formed by a partnership between the University of Texas at Austin and Gyeonggi-Do Province in South Korea. Through the GIP, Korean entrepreneurs attempt to expand domestically successful product ideas to the American market. The study results demonstrate that these innovators must deal with a broad range of challenges, particularly (1) developing deeper understanding of market needs, values, and cultural expectations, and (2) producing pitches with the structure, claims and evidence, and engagement strategies expected by American stakeholders. These studies confirm that a deeper understanding of successful new product development (NPD) projects requires not only a culturally authentic NPD process model, but also communication-oriented research.

The GIP approach offers insights into good programmatic concept and effective methods for training engineers to become entrepreneurs. Yet we also identify potential improvements for such programs. Finally, we draw implications for studying entrepreneurship communication.

Keywords

Entrepreneurship communication, pitching, market needs, value proposition

1 INTRODUCTION

Engineers, scientists, and other innovators sometimes develop what they consider to be a *good idea*: a technological breakthrough that they believe could have a significant impact in one or more industries. This good idea could be a *product* (such as a polymer-coated brake spring for the auto industry), a *process* (such as a new process for turning food waste into powder), or a *principle* (such as a newly understood magnetic principle that allows users to pulse a natural magnetic field on and off). But a good idea is not enough: the innovation must be communicated to potential users and stakeholders, and developed through market dialogue, in order to gain traction with a target market.

In this paper, we discuss our studies at the Gyeonggi Innovation Program (GIP), a program run by the Global Commercialization Group (GCG) at IC^2 in partnership with the Gyeonggi Small Business Center of South Korea (GSBC). In this program, innovators learn how to develop businesses based on technological innovations. Our studies examine how this program trains these entrepreneurs to communicate in global markets. We conclude with thoughts about how to develop the study and practice of entrepreneurship communication in related training programs.

2 BACKGROUND

2.1 The problem: Entrepreneurship communication

As the diffusion of innovation literature suggests [1], for an idea to be taken up by users in an industry, it must be adapted to their local needs. To actually offer value to industry, to create a commercialized technology that will be purchased and used by stakeholders (end users, channels, manufacturers, suppliers, etc.) in a market, innovators must engage in market dialogue that allows them to better understand these local needs and to position the innovation in a way that will address those needs. For instance, a polymer-coated brake spring may not seem useful to the auto industry if all it can offer is quieter brakes—but if it can offer increased safety and longevity of brakes, it becomes tremendously useful. By engaging in dialogue with automakers, the innovator can understand the pain points of their industry (such as safety) and can reposition the innovation in terms of rhetoric, use, and design.

If the innovation can be successfully repositioned, then it is turned into a *commercialized technology*. And the innovator is turned into an *entrepreneur*, someone who has successfully interposed himself or herself between a stakeholder and that stakeholder's needs.

However, most technological innovators find it difficult to make this sort of shift. The value of an innovative product or service comes from tying together contexts that may be unfamiliar [2], something that can only be done by engaging in market dialogue. Technological innovators often do not have the training to do this communication work, and they often find it difficult to understand the many genres (types of text) involved in it. In particular, they tend to have trouble with the genre of the *pitch*, in which an entrepreneur must articulate key claims such as the technology description, business model, team, and risks and barriers in ways that demonstrate the value proposition to a particular set of stakeholders.

2.2 Technology commercialization programs and consortia

To address this lack of training, many entities have established technology commercialization programs and consortia, often structured as pitch competitions. Such consortia, according to Gibson & Concelcao, attempt to "shorten learning curves and reduce errors" while "provid[ing] access to regional, national, and international markets, resources, and know-how" ([3], p.745; cf. [4, 5]). Such programs certainly emphasize understanding markets and developing value propositions that speak to the needs of target markets, typically providing actual market feedback. But when they help entrepreneurs formulate their arguments and revise them to address market feedback, such programs sometimes provide tacit, context-based support rather than explicit, systematic support. Furthermore, such programs tend to take on entrepreneurs operating in many different sectors, pitching to markets with differing regulatory constraints, competitive landscapes, business developments cycles, and margins; this wide variation makes it difficult to systematize pitch development, and consequently the training process emphasizes contingencies and draws heavily on the situated judgment of the mentors.

Indeed, when we began this research, we were surprised by how little systematic research there is on the pitch as a communicative genre—and the fact that none of this research seemed to examine pitch *development*, which is what these programs are meant to achieve. From 2013-2015, we conducted several qualitative studies examining how entrepreneurship communication was implicitly taught in the GIP, discussed below [6-11].

Such programs must teach innovators to not just *articulate* a value proposition but to *cocreate* it with stakeholders, including customers, partners, and others in the value chain.

2.3 Co-creating the value proposition

The entrepreneur's core argument is the *value proposition*. What do potential stakeholder groups value, and how can this innovation help them to address, achieve or hold share in that value? That is, what will convince them to become actual stakeholders? The value proposition explains what a product is, who the target customer is, and what value the innovator's firm provides. Geoffrey Moore says, "Positioning [value proposition] is the single largest influencer of decisions," yet "Even though positioning is one of the most discussed aspects of marketing, it is the least understood" ([12], p.48). Indeed, firms that hope to commercialize globally, such as those that participate in GCG programs, provide interesting cases, since globalizing naturally forces entrepreneurs to evolve their value propositions: as Moore argues, the value proposition must adapt if exposed to new conditions.

To better characterize the value proposition as a claim, we must understand the assumptions that underpin it. We turn to marketing theory, specifically service-dominant logic (SDL) [13-15], to characterize this logic.

Lusch and Vargo ([13], pp. 4-5) argue that marketing has assumed *goods-dominant logic* (GDL), in which value is understood as embedded in selling and transferring goods, described in generic market criteria: cost, quality, and speed. In *service-dominant logic* (SDL), use value is cocreated among all entities involved in the transaction, including customers but also others in the value chain. Thus value is assessed by criteria that are unique to a specific customer's needs. Critically, those needs are discovered through dialogue and feedback: although the firm may *propose* a value proposition, the customer *interprets* value proposition and provides feedback, which helps influence the creation of these solutions and experiences [16].

We can see the value proposition as a claim that can alternately function under two different logics. Under *GDL*, the claim describes how a *good's characteristics*, embedded by the producer, meet generic criteria. Under *SDL*, the claim proposes how a *service's benefits*, cocreated by the producer and customer, meet the customer's unique needs. By providing feedback on the value proposition, the customer plays an active role in co-creation [14].

Below, we draw on our recent studies to discuss how the GIP fostered entrepreneurship communication for addressing these challenges.

3 INSIGHTS FROM OUR STUDIES

3.1 Overview

We have published six studies on the GIP, investigating different aspects of entrepreneurship communication. In these studies, we interviewed program personnel and representatives of firms in the competition; video recorded practice and final pitches; and analyzed texts that were produced and used during two years of the competition. Methodological details are in our individual papers [6-11]; here, we overview findings across the studies.

The GIP is run by the Global Commercialization Group (GCG) of the IC^2 Institute, an interdisciplinary research unit at The University of Texas at Austin. GCG runs several such programs worldwide with local partnerships, helping to develop technology-based businesses by providing experience and training and facilitating links to international markets, with the goal of sustained commerce.

The GIP is structured as a five-phase program ending in a pitch competition. Each year since 2008, it has selected applicants from Gyeonggi Province with promising technologies, provided training and market information for innovators, and worked with promising innovators to help them connect with global target markets, particularly the United States. The GIP process includes these phases:

1. **Application**: Each year, the GIP receives over 200 English-language applications from entrepreneurs in the province; 50 are selected as quarterfinalists for the competition. Applications describe the entrepreneurs' technical innovations.

2. **Data Gathering**: This phase has two components: a dialogue between GIP managers and entrepreneurs, and an independent assessment of the market's interest in the innovation.

The GIP conducts "*Deep Dives*" with each firm: the firm mock-pitches to GIP analysts, using an initial deck based on the GIP's template. The firm also answers analysts' questions and takes the analysts on a tour of the firm's facilities in Gyeonggi Province. Finally, the analysts generate Deep Dive comments, which provide feedback and guide the GIP in selecting the semifinalists.

Experienced GIP contractors then write *Quicklooks*® assessing how well each technology can be commercialized in the target market(s). These 20-page reports recommend a "go" or "no go" for the specified market as well as actual quotes and market data from stakeholders in that market. Based on these Quicklooks®, the GIP selects 20-25 semifinalists to proceed to the final competition.

3. **Commercialization and Pitch Training**: The GIP program trains firms in various topics related to technology commercialization and pitch communication through classroom settings and individual mentoring. (Program training is ongoing and overlaps with other program phases.)

4. **Competition**: Semifinalists pitch to a panel of competition judges, using a final deck based on their initial deck but developed to address the Deep Dive comments and Quicklook® concerns. Of 25 semifinalists, 12-15 finalists are selected for extensive business development support in international markets provided by the GIP team.

5. **Business Development**: Finalists and GCG business mentors identify companies that might purchase, license, or commercialize the product.

These phases involve a large set of genres such as applications, reports, comments, deliberations, and presentations; these are generated by firms, the GIP, and competition judges.

3.2 Insight 1: Three transformations

Training programs should support different kinds of transformations: transforming the innovation, transforming the innovator, and transforming the cultural understanding of the target market.

At the GIP, the complexity of the process was compounded because one pitch competition served different innovation types (product, process, and principle), commercialized to different industries, addressing different markets, involving different business cycles. Yet the innovators had certain things in common. As they moved through the program, they faced three challenges:

Transforming the innovation. Innovators had to transform the innovation into a commercialized technology. That is, they had to reposition the innovation to better fit the needs of the market.

Transforming themselves. Innovators had to become entrepreneurs. That is, they had to learn the document genres that entrepreneurs use, but they also had to learn to think in terms of engaging in market dialogue to identify market needs.

Transforming their cultural understanding. Finally, innovators had to be flexible enough to identify and address audiences' cultural expectations. For instance, informants said that Korean entrepreneurs tended to focus on fulfilling cultural values such as respect for position and social contract, while US-based audiences tended to expect market-oriented arguments focusing on profits and market share. To pitch successfully to US audiences, innovators had to use persuasive tactics that might be unsuited to their own cultural context. For example, innovators were used to focusing on improvements to cost, quality, and speed due to Korea's focus on import replacements; US audiences, tended to expect value propositions that offered something beyond these three criteria.

These three challenges were not distinctly articulated in the GIP [10].

3.3 Insight 2: Extended set of stakeholders

Another challenge is to understand how factors, such as market sector, kind of innovation, size of firms, and stakeholder values, impact innovators' needs. Can one program address all innovators or do they need tailored training programs?

In principle, the GIP serves small and medium businesses operating in different sectors, offering different kinds of innovations. But in practice, the program filtered out innovators whose innovations did not align with the GIP's own set of stakeholders. The most successful entrepreneurs in the GIP were those who addressed the GIP's own stakeholders as well as the nominal stakeholders (potential partners, investors, or distributors to whom the pitch was aimed) [10]. GIP stakeholders included public (government), private (business), and academic (higher education) sectors. As the Director told us, the three sectors had different expectations.

Public sector: The GIP was supported by the GSBC, established by the governor of Gyeonggi-Do Province. Thus the program ran on annual funding cycles: the GSBC expected to generate annual media events to tout "concrete, demonstrable results" such as export revenue.

Private sector: This followed variable cycles. For instance, the automotive industry is driven by a 3 to 5 year sale cycle due to certification, design, and testing requirements. Health care and food industries also face long cycles due to certification. Other industries have shorter cycles. Since the small and medium enterprises (SMEs) applying to the GIP operate in a variety of industries, they had to follow a range of business cycles. The GIP provided external validation for these innovations.

Academic sector: This was inwardly focused, operating on a longer cycle. GCG focused on "an education-capacity-building-driven model." These stakeholders benefited through royalties supporting research programs and benefiting inventors.

Ultimately the program was built around the public-sector cycle, and in the Director's judgment, this annual cycle led to "unnatural behavior." For instance, the program had to prioritize firms that have already commercialized their products in Korea: those firms had already learned how to package, deliver, and provide customer support for products, so the learning curve for global markets was shallow enough to fit into the annual cycle.

Since these stakeholders had different interests, competitors had to address criteria beyond those of their nominal stakeholders. Not only did they have to address these criteria in their initial argument (the application), they had to keep their argument coherent even as they adjusted it to address the feedback of their nominal stakeholders (potential partners, investors, or distributors). In practical terms, training programs might consider developing a specialized focus to better surface the criteria and stakeholders that innovators must address.

3.4 Insight 3: Feedback loops

Feedback seems to be a key success factor for co-developing successful pitches and convincing claims. Training programs should train the ability to produce effective feedback (cycles) as well as to use the feedback in a highly productive way.

The GIP provided multiple feedback avenues: Deep Dive comments, training (including pitch training), Quicklooks, and Q&A during the final pitch. These feedback avenues are important for innovators, who must iterate their innovations; the innovators also need guidance in applying this feedback.

Each feedback avenue provided a different perspective. But since feedback came from different quarters (business analysts, trainers, representatives of the market), it addressed criteria and interests of different stakeholders. This feedback was not well differentiated in the GIP, so stakeholders had limited guidance as they attempted to address different sets of criteria while keeping their pitch arguments coherent [10, 11].

Indeed, we found that the business analysts who authored the Quicklooks themselves had to revise their documents, sometimes repeatedly, to address concerns of the Director and express clearly the voice of the market [6]. The ultimate quality of these Quicklooks depended on this feedback process, in which the analysts had to refine their analyses and sometimes go back to the market representatives for clarification. As we discuss in [6], analysts require training to write these Quicklooks well, since the quality of the Quicklook guides the judges in selecting technologies for development.

Beyond gaining different perspectives, entrepreneurs also had to incorporate that feedback. We found that many would copy Quicklook feedback verbatim into their slides, and some would also paraphrase and expand on that feedback; a few would actually quote and rebut that feedback, which represented a more sophisticated strategy [9]. In our observations of pitch training, we found that the trainer provided some advice on incorporating and rebutting difficult Quicklook feedback, but did not have a chance to examine how it was finally incorporated by the entrepreneurs before the final pitch [11]. Unfortunately, the entrepreneurs were not presented with the Quicklooks until just after pitch training, meaning that they had only two weeks to incorporate the Quicklook feedback into their final pitches. We believe this short timeline impeded their ability to address this feedback. Innovators need feedback and time and guidance to incorporate it.

3.5 Insight 4: Genres' roles in making transformations

Entrepreneurship communication is based on and empowered by *genres* (text types) [8, 9], and programs should enable actors (entrepreneurs, trainers, experts) to use these genres effectively.

Innovators had to compose some genres (applications, pitch decks) and read others (Deep Dive comments, Quicklooks). In learning these genres, the entrepreneurs also (to some extent) learned the genres' activity orientation. That is, learning these genres helped innovators to become entrepreneurs, to think of their innovations as commercialized technologies, and to learn about the culture of the nominal stakeholders.

For instance, all entrepreneurs had to follow the pitch deck template. GIP personnel said that these entrepreneurs were not yet used to thinking in terms of global markets, particularly the US market, which was more oriented to profits than other values [8]. The pitch deck guided these entrepreneurs in making claims that they might not otherwise have made, but that were expected by the target market. In one example, the last slide in an initial deck described how the innovator could win a Korean business award [8]. In the final deck, the slide was replaced by slides that were more meaningful for the target market: market interest, competition, risks and barriers, and team status.

Genres also interacted: innovators reused text from genres they wrote and read. Resulting pitch decks tended to modify claims and evidence, and some included rebuttals to the Quicklooks [8].

During pitch presentation training, the trainer often corrected entrepreneurs on how they structured their overall arguments and how they formulated and supported individual claims [11]. Thus innovators received further guidance in composing this key genre. For instance, one firm was advised to quote criticisms from the Quicklook report and provide explicit rebuttals of those criticisms with evidence from other documents.

Innovators need training to better understand, use, and produce genres, and specifically, training in developing pitches for different audiences: a Korean pitch is not the same as a US pitch.

3.6 Insight 5: Three tactics for repositioning: Rhetoric, use, and design

Entrepreneurship requires tactics for repositioning innovators' rhetoric, use and design to fit the values and expectations of their target market.

Entrepreneurs can address resistance from market representatives via *design* (redesigning the innovation's features and performance); *use* (repositioning the innovation for a new market segment and associated application); and *rhetoric* (refining or changing the argument for applying a design to a use to realize market value). With more time and greater resources, innovators in the GIP might have chosen to adjust design or use. But in the pitch competition, their only real recourse was to adjust their rhetoric for applying the design to the identified use in the market [7]. We saw several instances during the competition in which entrepreneurs refined rhetoric [8, 9, 11], but no instances of refining the proposed design or use.

However, pitch competition winners were then mentored in business development, in which they could enact refinements in design and use as well as rhetoric. That is, during the competition, they learned the genres and underlying logic of global entrepreneurship as well as how to understand and incorporate feedback. Once they had learned to argue, they could also address use and design.

3.7 Insight 5: Shifting between GDL, SDL—and VDL

Entrepreneurship often begins by describing a solution to an assumed problem, but then shifts to proposing a solution to an emergent problem. The innovators who were able to make this shift tended to do better in business development.

According to business developers who mentored during the business development phase, entrepreneurs typically began the GIP with GDL-based value propositions, *describing* a solution to a predefined problem. But by the time they finished the GIP, many entrepreneurs shifted to SDL, *proposing* a solution to an emergent problem, based on ongoing dialogue with stakeholders conducted via feedback loops. This ongoing dialogue allowed them to *cocreate* [14, 16] a value proposition with the customer by generating a set of criteria that uniquely address the customer's needs [7].

Once we examine the value proposition as a claim, we can better understand how such claims are positioned and thus how to help develop entrepreneurs' rhetorical expertise. But entrepreneurs must *also* develop other tactics in their repertoire, such as use and design; a good argument for the current state of the innovation is no substitute for an iteration of the innovation itself.

We also argue that GDL and SDL perspectives do not adequately characterize NPD outcomes, which are typically commercialized through intermediaries in an economic ecosystem. Thus the product's value proposition must directly benefit the intermediary through whom value is passed to the end user and with whom value is shared in terms of sales receipts, royalties, etc. Expressing such a value proposition does involve GDL (products, units) and SDL (user value recognition, options, pricing based on fit, outcomes). But it also must discussing value *across* the value chain, addressing issues such as differentiation, intangible assets and outcomes, and competitive edge. In subsequent papers we plan to develop a better understanding of this *Value-Dominant Logic* (VDL).

4 CONCLUSIONS

Our studies suggest that entrepreneurship communication is vital, but is generally taught tacitly, through models and situated advice. At the same time, the GIP is structured so that rhetoric is the only avenue for addressing resistance from market representatives. We believe entrepreneurship communication can be more systematically taught in such programs and integrated with other avenues.

NPD processes require culturally authentic NPD process models and research incorporating the perspective of communication [6; see also 17]. We believe our work can provide insights to other programs as they develop their NPD models.

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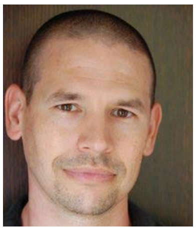

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"Overloaded, Slow, and Illogical" A Usability Evaluation of Software for Product Manufacturing Processes with a Special Focus on Age and Expertise of CAM Users

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Abstract
Today's manufacturing processes require complex computer-aided planning processes, which are provided by CAM (computer aided manufacturing)-software systems. While the functional capabilities of these systems are constantly extended, less attention was paid to CAM-software usability. Facing the demographic change (cognitively aging users, retiring of experienced CAM experts who are succeeded by inexperienced users), not only usability issues but also user-specific requirements are becoming increasingly important. An online-survey regarding the usability of CAM-software was conducted (n = 76) and - apart from general usability - effects of age and CAM expertise were analyzed. Main usability barriers were program behavior and controllability. For older and inexperienced users, cognitive complexity (menu complexity and information density) was found to affect productivity and satisfaction of CAM-software usage. For younger CAM experts, an improved system support (feedback, search function) in solving CAM problems was identified as important requirement. Recommendations for a user-centered CAM-software usability optimization were derived.

Keywords
Computer-aided engineering software, usability, user diversity

1 INTRODUCTION

Automated product manufacturing processes require complex computer-aided planning processes that are facilitated by CAx-software systems (computer-aided technologies). These software systems are highly complex and place considerable demands on users' domain-specific knowledge and software tool expertise. The increasing complexity of CAM-software systems, on the one side, and the changing structure of the workforce due to the demographic change, on the other, highlight a research issue that has been rarely considered so far: the usability of CAM-software systems and changing requirements of an increasingly diverse workforce.

The invention of computer-aided design (CAD) and computer-aided manufacturing (CAM) systems in the 1950s [1], combined with the computerization of numerical control (CNC) for machine tools, mark the beginning of computer-aided engineering (CAE). While first computer-aided systems were isolated solutions, the logical development led to integrated solutions, since design (CAD) and manufacturing (CAM) are closely connected or even interacting procedures in the CAx process chain [2] (Figure 1).

This trend from traditional to CAE, driven by the improvements in digitalization, processing power, and the invention and mass distribution of the personal computer, triggered the boom of CAD/CAM-software in the late 1980s [3].

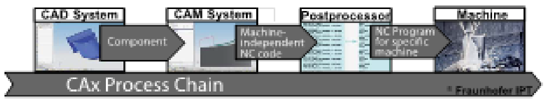

Figure 1 - CAx process chain.

Since then, with increasing requirements to the software by integrating CAD, CAM, computer-aided process planning (CAPP), and several other simulation features like FEM, CFD, etc., the amount of functions has constantly risen, all summed up as CAx [4].

The broad functionalities provided by CAx systems come at a price: the software tools have become highly complex. The increasing number of machine tools and their functions (multiaxle positioning systems, inventions of new milling heads for new and faster machining of more materials, etc.) permanently required software extensions and updates. Even with standardized tools and functions, the complexity of CAD/CAM-software has already risen to a level where only highly trained experts are able to use current CAD/CAM-software. While new production technologies like adaptive manufacturing adopted functionality and user interfaces from established CAD/CAM-software, the development of computer-integrated manufacturing (CIM) - the simulation of the entire production process and organization with fully integrated CAx-features - will boost complexity to an even higher but also inevitable level if manufacturers want to stay competitive [5].

2 CAM-SOFTWARE USABILITY AND USER DIVERSITY

So far, the improvements of CAM-software have mainly focused on technical optimization and compatibility along the workflow [6]. New functionalities were added to the CAM interface without considering a general usability framework. Even though software developers have put a lot of effort into redesigning and optimizing GUI usability of other software products since the mid-1990s [7], along with the development of an industry standard for ergonomic dialogue design (ISO EN9241) [8], usability aspects for CAD/CAM-software have been disregarded so far. Considering the increasing complexity of CAM-software, the quality of interface design, measured by its usability, becomes more and more important as a competitive advantage. The usability of a system is defined as “the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction” [9]. However, existing UI principles are mostly too generic for complex CAM software, since they are mainly directed on desktop (e.g. text editors) or web applications [10]. Therefore, CAM software requires a refinement of UI principles.

Apart from general CAM system usability, the impact of user diversity factors (e.g. CAM expertise) on a successful CAM-software interaction also needs to be considered. Since CAD/CAM-software can hardly be intuitively used but requires both users’ domain-specific knowledge and software tool expertise, novel CAx-users usually receive extensive CAx-software trainings. However, practice shows that CAM novices are not able to successfully handle the CAx-software, which leads to longer training periods and frustration on the users’ side and to inefficient allocation of resources, reduced product quality, and delivery delays on the business side. Facing the demographic change and its consequences for the workforce using CAM (cognitively aging users, retiring of well-trained and experienced CAM experts who are succeeded by inexperienced CAM users), future CAM systems should be designed and optimized in a user-centered way to meet the demands of an increasingly heterogeneous user group [11] with differing levels of CAM expertise and cognitive skills. For this reason, the motivation of this study was an evaluation of CAM-system usability as well as a detailed analysis of the effects of age and CAM-expertise on usability barriers of CAM-systems. The following research aims were pursued:

1. Evaluation of general CAM system usability: What are the main usability barriers perceived by users?
2. Evaluation of general CAM system productivity and satisfaction: How do CAM users judge their efficiency while using their CAM-software and how satisfied are they?
3. Impact of user diversity: How do users of different ages or expertise vary in their evaluations and which specific requirements do different user groups have?

3 METHODOLOGY

3.1 The questionnaire

Based on a usability prestudy (interviews with three CAM users) and the analysis of established usability inventories based on DIN EN ISO 9241 [8], the questionnaire was developed. It contained a *demographic section* (age, gender, education, profession) as well as items regarding *CAM expertise* (type of CAM system, usage experience in years, usage frequency, self-ratings of CAM system knowledge and problem-solving competency), CAM system *support*, and used and preferred ways of *CAM knowledge acquisition*. In the *usability evaluation* part, ratings of the efficiency and satisfaction of CAM-software usage as well as key usability criteria (feedback, naming, menu Design, search function, information presentation, icon design, color use, error avoidance, program response) were assessed by using 6-point Likert-scales. Respondents could enter further usability barriers as text comments in comment fields. Usability criteria were selected according to their relevance to CAM usability problems mentioned in the prestudy. Usability criteria scores were calculated by building the means of single usability items. Construct reliability measured by Cronbach’s alpha was above 0.7 for all usability criteria.

3.2 The Sample

The online-questionnaire was distributed in several German manufacturing companies and in CAM-related online forums. $N = 119$ participants took part in the study, but only $n = 76$ data sets were used for statistical analysis due to incomplete data.

Respondents’ age ranged from 23 to 62 ($M = 41.1$, $SD = 10.5$), nearly all (97.4%) of the participants were male. Regarding the level of education, 36% held a university degree, 30% completed an apprenticeship, 17% had a secondary school degree, and 14% a technical diploma. Half of the participants (49%) were software developers, 24% technical draftsmen, and 21% were toolmakers. The usage experience was between 2 months and 39 years ($M = 8.1$ years, $SD = 6.9$) and the CAM-software was quite frequently used (73% several times a day, 21% several times a week). The majority (43%) worked with Siemens NX, followed by Tebis (8%), CATIA, and SolidCam (both 7%). Since the study focused on a general usability evaluation, no comparisons between different CAM-software solutions were made.

Data was analyzed by MANOVAs, correlations, and regression analyses; the level of significance was set at 5%. The Likert-scale range was transformed to -2.5 (totally disagree) to 2.5 (totally agree) with ratings < 0 indicating negative evaluations and ratings > 0 indicating positive evaluations.

4 RESULTS

First, the results regarding general CAM system usability are reported (5.1), followed by a detailed analysis of user diversity factors (5.2), and a regression analysis (5.3).

4.1 CAM system usability

The general CAM system perception was positive. CAM users reported a high work efficiency (M = 0.95, SD = 1.23), a high ease of use (0.93, SD = 1.18), and satisfaction (M = 0.81, SD = 1.08) in using their CAM-system.

Looking at general CAM system usability, the majority of criteria was positively rated (Figure 2).

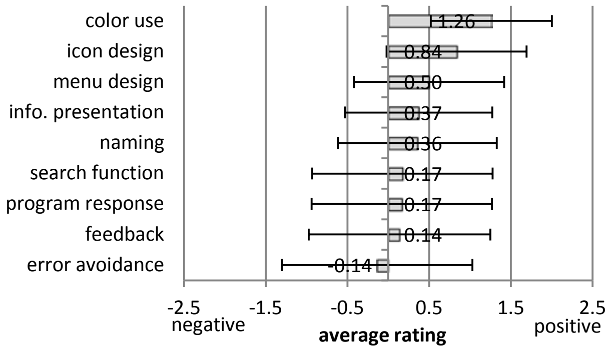

Figure 2 - Mean CAM usability criteria scores (n = 76).

The use of colors in CAM-software was mostly positively evaluated (M = 1.26, SD = 0.74), followed by icon design (M = 0.84, SD = 0.86), menu design (M = 0.5, SD = 0.92), information presentation (M = 0.37, SD = 0.9), naming (M = 0.36, SD = 0.97), search function (M = 0.17, SD = 1.10), program response (M = 0.17, SD = 1.10), feedback (M = 0.14, SD = 1.11), and error avoidance (M = -0.14, SD = 1.17). However, only two criteria ("color use" and "icon design") received on average affirmative ratings (> .8); the evaluations of the other usability criteria were only slightly positive (> 0.5) or even negative for the criteria "error avoidance." Moreover, the usability criteria evaluations show high standard deviations (between 0.74 to 1.17), which implies that CAM users strongly differed in their perception of CAM system usability. Therefore, the following section focuses on the effects of user diversity, i.e., CAM users' age and expertise, to explain discrepancies in usability evaluations.

4.2 User diversity: effects of age and expertise

To analyze effects of age and expertise, the sample was divided into different subgroups according to age (young = 23-34 years, middle = 35-45 years, old = 46-62 years) and expertise. To quantify expertise, an expertise score was calculated based on the multiplication of subjective ratings of "CAM knowledge" and "problem-solving competency" (M = 1.94, SD = 2.18, min = -6.25, max = 6.25). Two expertise groups were derived: *novices* with an expertise score < 0 and *experts* with an expertise score > 3.75. Novices had on average M=6.2 years (SD=5.4) and experts M=9.6 years (SD = 7.8) of CAM usage experience. A longer duration of CAM usage in years was associated with higher expertise levels (r=.24; $p < 0.05$). Age and expertise (measured by the expertise score) were not correlated (r =.19; p>.1), which indicates that age and CAM expertise were independent from each other.

A 2x2 (age x expertise) MANOVA of ratings of efficiency and satisfaction revealed a highly significant main effect of expertise ($F(2,36) = 14.18$; $p < 0.000$) and an interaction between age and expertise ($F(4,74) = 3.67$; $p < 0.01$; Figure 3).

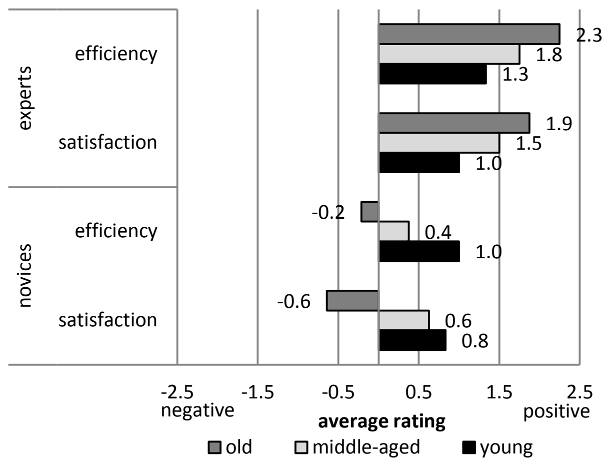

Figure 3 - CAM efficiency and satisfaction ratings for different age- and expertise groups.

Novices reported to be significantly less efficient and satisfied when using their CAM-software (efficiency: $M_{experts}$ = 1.8, SD = 0.94; $M_{novices}$ = 0.36, SD = 1.0; satisfaction: $M_{experts}$ = 1.5, SD = 0.7; $M_{novices}$ = 0.26, SD = 1.1). Looking at the interaction between age and expertise, reported satisfaction and efficiency was extremely low (or even negative) among older novices and extremely high for older experts.

A similar pattern was found for CAM usability criteria ratings. Novices gave lower CAM usability ratings than experts ($F(1,38) = 2.69$; $p < 0.05$). The criteria naming, menu design, icon design, error avoidance, program response, and info presentation were evaluated as less user-friendly (Figure 4). Severe usability barriers for novices (indicated by negative evaluations) were error avoidance, program response, and search function. No age differences were found for CAM usability evaluations.

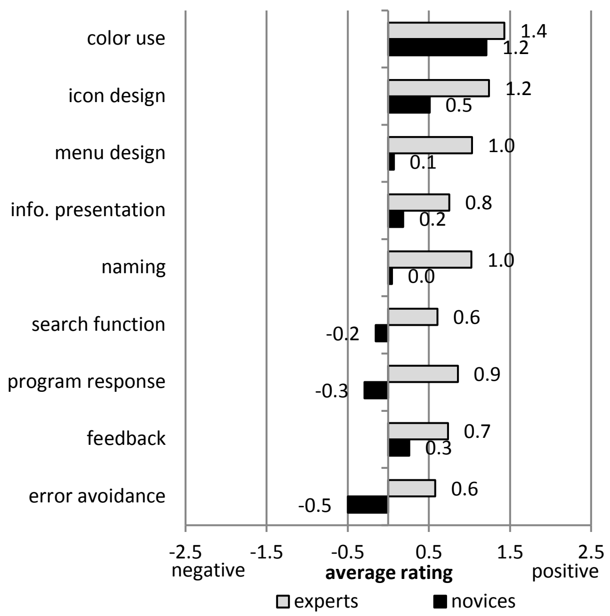

Figure 4 - CAM usability criteria ratings for CAM experts and novices.

The interaction between age and expertise ($F(18,44) = 1.9$; $p < 0.05$) indicated that especially older CAM novices perceived a lower usability of their CAM-software, except for the criteria “icon design” and “error avoidance”, where the evaluations of the age- and expertise groups did not differ (Figure 5).

The most noteworthy results of the age x expertise interaction will be outlined here: Except for color use, older novices evaluated all usability criteria negatively, especially program response and menu design. Interestingly, search functions were evaluated more negatively by younger novices. In contrast, especially young CAM experts complained about bad system feedback and middle-aged experts negatively evaluated the search functions.

4.3 Regression analysis

So far, results showed that user factors strongly affect CAM-efficiency, -satisfaction, and usability perceptions. To investigate the relationship of these variables, multivariate regression analyses were conducted. Regression analysis is a statistical tool for the investigation of relationships between variables. To analyze which CAM usability criteria predict perceived efficiency and satisfaction among CAM users, stepwise age-specific regression analyses were run. Condition indices < 10 showed that regression models were not biased by effects of multicollinearity due to interrelated predictor variables.

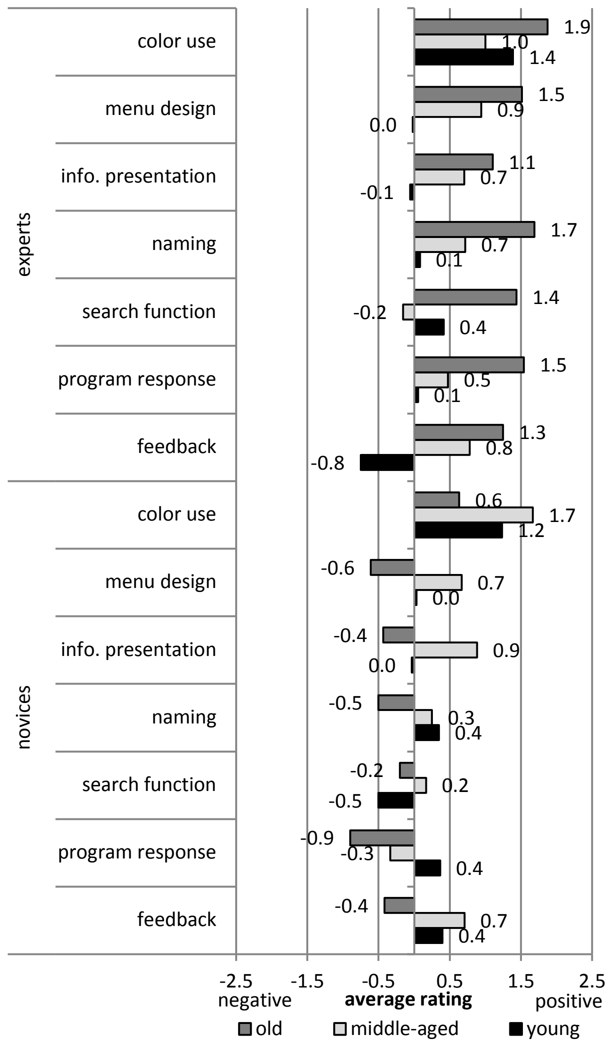

Figure 5 - CAM usability criteria ratings for different age- and expertise groups.

The regression models for predicting *efficiency* of CAM-software usage with usability criteria as dependent variables showed that the criterion “program response” was the only predictor, which explained CAM efficiency ratings in young (ß=.54) and middle-old users (ß=.69). For young CAM users, the proportion of explained variance (R^2) for CAM efficiency was only 25%, for middle-aged CAM users it was 44%. For older CAM users, a different pattern was found: not only “program response” (ß=.8) but also “information presentation” (ß=.86) and “menu design” (ß=.73) explained 89% of CAM efficiency ratings in older CAM users (Figure 6). This shows that perceived efficiency in older users is not only determined by program response issues but also by aspects of cognitive complexity, i.e., menu complexity and information density of CAM-software design.

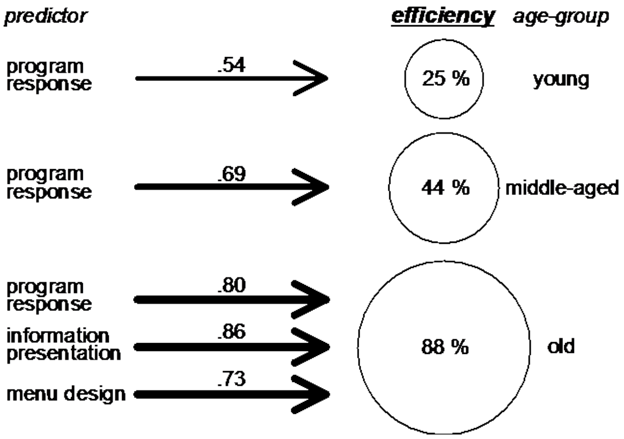

Figure 6 - Age-specific stepwise regression analysis on efficiency (R^2 in % circles, ß-coefficients above arrows).

A comparable pattern was found for the prediction of CAM-*satisfaction* ratings. CAM satisfaction in younger and middle-aged users could only partly be explained by usability criteria (R^2=21% for young users and R^2 = 25% for middle-aged users), namely by color use (young group, ß=.51) or program response (middle-aged group, ß=.54). For older users, satisfaction was strongly affected by usability criteria (R^2=89%), i.e., by program response (ß= .89), information presentation (ß=.84), menu design (ß=.61), and search function (ß=.35, Figure 7).

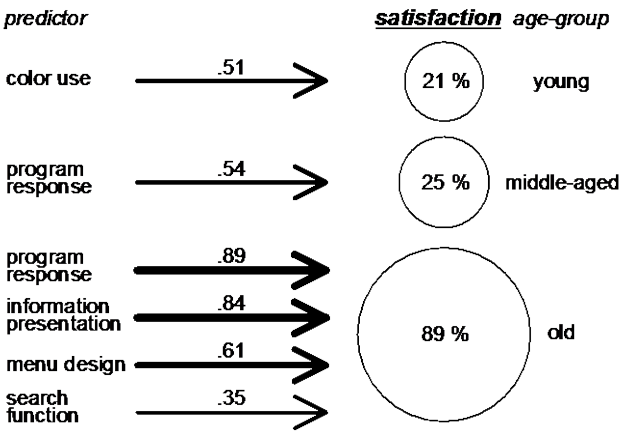

Figure 7 - Age-specific stepwise regression analysis on satisfaction (R^2 in % circles, ß-coefficients above arrows).

5 DISCUSSION

Today's manufacturing processes require complex computer-aided planning processes. While the functional capabilities of CAM-systems are constantly extended, less attention has been paid to their usability. Facing the demographic change, not only usability issues but also user-specific requirements should be considered. Therefore, a survey regarding the usability of CAM-software was conducted (n=76) and –apart from general usability-effects of user age and CAM expertise were analyzed.

5.1 General usability considerations and recommendations for CAM-software

Although the usability evaluations of CAM-software were positive and users reported to be generally satisfied and productive with their CAM-software, a deeper look at specific usability criteria revealed main starting points for an optimization of CAM-software. Hence, optimization activities should be directed on aspects of *error avoidance* (automatic caching, explicit warnings prior to important events, going back to previous steps without losing data entries), *feedback* (reliable, comprehensive, and timely feedback), *program response* (knowledge if the program is still running or has crashed, having full control over every step in the procedure), and the *search function* (context-sensitive search, clear presentation of search results). In contrast, graphical design aspects of CAM-software interfaces such as color use or icon design were not perceived as relevant barriers. Accordingly, CAM-software optimization activities should not be directed on "cosmetic GUI improvements" of color, font size, etc., but they should focus on program behavior and controllability. Moreover, the integration of user diversity factors yielded further recommendations for CAM-software optimization.

5.2 User-specific requirements for CAM usability

The user-centered analysis in this study revealed that two main future CAM user groups, i.e., older and/or inexperienced users, have specific requirements regarding CAM-software usability. As the regression analysis for *older CAM users* showed, not only aspects of program behavior but also aspects of cognitive complexity, i.e., menu complexity and information density, affect satisfaction and productivity of CAM usage among older users. The interactions between age and expertise imply that cognitive complexity affects most older novices. Human factors research [11], [12] suggests that cognitive complexity in GUI design can no longer be compensated by the cognitive system of the aging user. Accordingly, CAM systems should be designed in such a way that cognitive complexity is reduced, e.g., by simplifying menu structures and using users' mental models for designing task procedures [13].

The user group that needs the most consideration and support was the group of older *novices*, i.e., older users with low CAM expertise. Accordingly, not only the CAM GUI but also knowledge support such as training, software-immanent tutorials, or online knowledge communities should be improved and established in order to avoid longer training periods and frustration for the user and inefficient resource allocation on the business side. The negative evaluation of search functions by younger novices suggests that younger novices could also benefit from an improved CAM-software immanent knowledge support. In contrast, the findings for the group of *older experts* showed that expertise can moderate age effects with regard to perceived usability barriers, satisfaction, and efficiency of Cam-software usage. Companies should therefore systematically use this valuable CAM-knowledge source of older users and establish knowledge transfer structures in which experts accompany the "onboarding process" of novel CAM users by giving support in CAM-knowledge acquisition and problem-solving.

5.3 Limitations and future research questions

The present study should be replicated with a larger sample, which allows for a more detailed analysis of age- and expertise subgroups as well as a benchmark study with regard to different CAM-software systems. Future research activities should also be directed on a GUI redesign and evaluation – especially focusing on cognitive ergonomics of CAM-software – under consideration of age- and expertise-specific user requirements.

6 ACKNOWLEDGEMENTS

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8 BIOGRAPHY

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Emerging Synthesis of Social Manufacturing

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Abstract
Manufacturing systems has changed constantly throughout the years and new theory towards value creation is emerging. The latest manufacturing paradigm is described as social manufacturing which uses open design platforms. Open design platforms could give the hands of every individual the means to produce physical objects or products. Nowadays, with the wave of the Internet of Things (IoT) people can participate from global communities to contribute to the innovation process. Everybody can use existing design tools and solutions on open platforms. This will ensure co-creation to produce even more solutions. Social manufacturing harnesses the emerging synthesis from open design platforms and the manufacturing capability that is embedded within the online community platform, whereby the users co-manufacturer their own products. This paper discusses an one week challenge case study that investigates the possibility of completing the open design process of a product during a limited timespan using social manufacturing techniques. This case study proved that a product can be crowd sourced and delivered within a week. These results showed that the desired industrial cluster could be reached. These social elements are promising for future manufacturing businesses.

Keywords
Social manufacturing, Crowd sourcing, Open design

1 INTRODUCTION

Manufacturing has been fundamental to prosperity and national development. A strong manufacturing platform is important to any community or society, because it contributes to all the other sectors of the economy. This means manufacturing deserves strong endeavour of all factors in modern society to ensure better life, prosperity and sustainable development. There have been many revolutionary changes to manufacturing throughout the years as illustrated in figure 1. According to Koren *et al.* [1] the change in the manufacturing paradigms are caused by changes in societal and market imperatives, and the development of new enabling technologies.

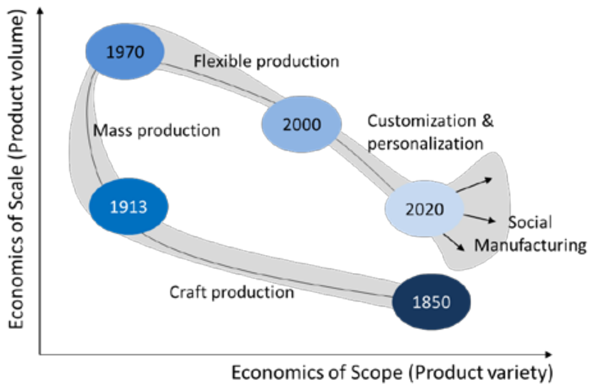

Figure 1 - Change in manufacturing paradigms with regards economics of scale and economics of scope [2]

The craft production paradigm enabled society to focus more on the economics of scale. This paradigm was supported with the invention of assembly lines. Around the 1970's the market was saturated with specific products, which was mass produced, and society demanded greater product variety. Thereafter, we moved into this era of customization and personalization. However, there is a new manufacturing revolution on the horizon and it is called social manufacturing. Manufacturers will produce products on social manufacturing platforms, while new small companies or local suppliers and customers will develop the products using open design platforms [2].

The latest Internet of Things (IoT) industrial revolution [3], [4] have ignited manufacturing strategies in countries around the world such as the Catapult (UK), SIP in Japan, Industry 4.0 (Germany) [5], [6], [7] and NNMI (US). Kagermann *et al.* [8] describe this revolution as the convergence of the virtual world (cyberspace) and the physical world in the form of Cyber-Physical-Systems (CPS). This era of manufacturing will bring changes in production methods, customer expectations and value creation. Due to these changes, Burmeister *et al.* [3] stated that the focus point should move from product and service innovation to business model innovation.

A case study is required in order to understand the business model of social manufacturing. Therefore a experiment is needed where a community or industrial cluster is used within a manufacturing process. An industrial cluster is the "social community and economic agents" [9] that collectively strives to produce a superior product and/or service. A social community is an ever-changing body of people. Thus, by using a social media platform, their idea creation, knowledge and niche-spotting capacity could be harnessed to address seemingly overwhelming problems.

However it is very difficult to build a company around the idea that "The faster the product is produced, the more there is time to produce the next product". Ben Kaufman, the founder of Mophie, launched Quirky in 2009 and had this mentality. Quirky was a start-up that "…pledged to help regular people turn their ideas into real products and sell them in stores nationwide" [10].

Value creation within social manufacturing cannot be described as a traditional process, where the consumer and the producer are separated from each other. Instead the consumer changes his role into a development competence consumer or prosumer [11]. The open design principle for value creation within social manufacturing follows a bottom-up approach [12] from which different types of patterns emerge where the underlying theory in this process is called, Emerging Synthesis [13]. Therefore using this case study as a social manufacturing experiment, patterns can emerge to use social media in the manufacturing process.

2 SOCIAL MANUFACTURING

Social manufacturing relies on the premise that personal and social networking relationships and ties provide value to organizations in a network by allowing them to tap into the resources embedded within the network for their benefit [1]. Zhang *et al.* [14] define social manufacturing as a new kind of networked manufacturing mode which integrates plenty of distributed socialised manufacturing resources and aggregates enterprises into manufacturing communities through initial clustering and self-organisation. Vukovic *et al.* [15] believe that web 2.0 technologies are the enabler of crowd sourced manufacturing.

The idea of open design platforms is to change the way we construct knowledge around manufacturing itself, as the ability to generate new knowledge can have a significant role to stay competitive [16]. This leads to new methods in the way we solve problems and accelerate the process using of co-creation [8]. Social manufacturing is predicted to be used by the year 2020. The business model will use a pull (sale-produce-assemble) system as shown in Figure 2. Society will be sustainable conscious across the total value chain and will demand personalised products. The enabling technology for social manufacturing will be the internet of things and the key technology can be self-organizing systems. Information and knowledge processing will be based on cyber-physical systems.

Paradigm	Social Manufacturing		Existing Social Manufacturing companies
Paradigm begin	2020		Local Motors
Societal Needs	Personalised products on demand –Sustainability conscious		Opendesk
Market	Global production – demand fluctuation		Quirky
Business Model	Pull (sale-produce-assemble)		Shapeways – 3D printing
Enabling Technology	Internet of things		WindowFarms
Key technology	Self-organizing systems		Blender
Information & knowledge processing	Cyber-physical systems		OpenStructures

Figure 2 - Social manufacturing elements (Adapted from [2])

Social manufacturing creates opportunities for internal related work or with corporate partners to have seamless access to relevant information, transfer and share documents and to automate manual tasks that can accelerate processes and decision making.

The difference between conventional manufacturing and social manufacturing companies is that anyone that has internet access can create and share their ideas or product designs online in an open design database. Once they have shared a design or idea, other people can contribute to the design by either making suggestions or improvements. Using more crowd sourcing and customer immersion service platforms in social manufacturing to identify patterns from emerging synthesis will shorten the design period. This will ensure faster identification of the required patterns and will help to develop customer demanded products. The second mayor difference of social manufacturing is that the manufacturing is done by the user/market and the manufacturing capability is embedded within the online community platform database. Social manufacturing will enable companies to design and prototype products faster, with access to more human resource on a platform at a lower cost than their competitors as illustrated in Figure 3.

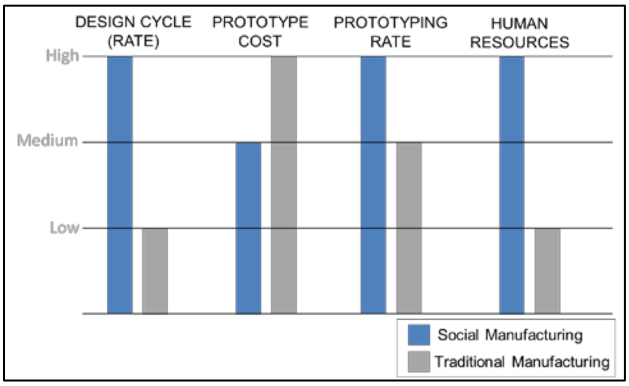

Figure 3 - Comparing efficient utilization of social- and traditional manufacturing methodologies (not to scale – for illustrative purposes only) [2]

3 RESEARCH METHODOLOGY

The one week challenge goal is to use Social Media to complete the entire manufacturing process within a week. This is done by gathering data on the implementation of social manufacturing in an industrial cluster, such as the Industrial Engineering Department of Stellenbosch. With the use of social manufacturing the abstract design phases should become shorter as shown in Figure 4.

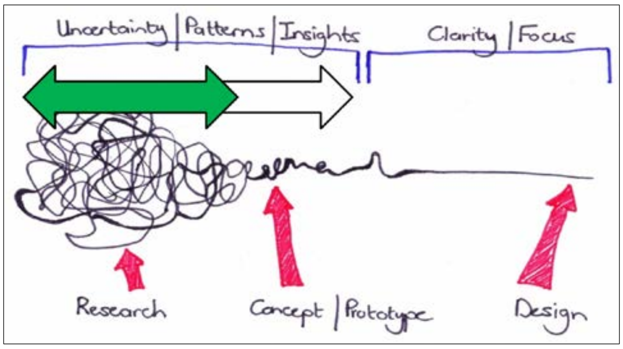

Figure 4 - The effect of open design on the design process during product development [2]

This can lead to a faster identification of market and customer requirements which decreases the manufacturing process time. Using the concept from Figure 4, a framework was developed for the one week challenge as illustrated in Figure 5.

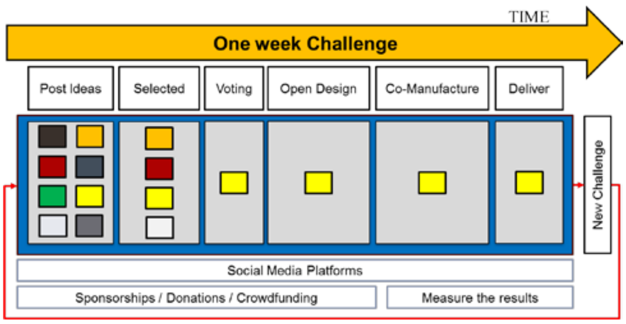

Figure 5 -One week challenge framework illustrating the community selection, open design and co-manufacturing process steps

The one week challenge starts by posting a problem on Social Media. Crowd sourcing starts where people posts ideas as possible solutions, the best ideas is used in a voting pole. The winner from the voting pole is then used as the product that needs to be manufactured. This entire process happens in one week from the initial idea sourcing to the delivery of the manufactured product as illustrated in Figure 5. After the final product is delivered a new problem is posted on Social Media, then the process is repeated.

In order for the one week challenge to be successful, a few requirements were set:

- Keep the product functionality simple
- Use 3D-printing in manufacturing process
- Use social media to develop the final specification for the product
- Try to use the least amount of resources
- To deliver the packaged product within the time period.

A description on the proceedings of the one week challenge day by day will follow below.

3.1 Monday: Establish Social Media platforms

The goal of the first day was to set up the project on various social media platforms, and present with content that the industry cluster could relate to. To attract participation to this project, Facebook and Instagram accounts where used to exchange information with the industrial cluster. This project description was fully described in text format on the separate accounts, but made use of graphics and short videos to amplify its appeal. The secondary goal of the first day was to establish a connection with the industrial cluster and to encourage engagement. This was the most challenging task of the week and could be a crucial task for any social manufacturing project.

3.2 Tuesday: Product Specification

The second day was dedicated to understanding what the industrial clusters' needs are, and how to meet them. Evaluation of their input on the social media platforms with regards to the initial published solutions which purpose was to stimulate engagement.

This process was dependant on the reach and followers gained on the first day on the Social Media platforms. Where the previous goal was to get followers on the Facebook and Instagram accounts, the second day's goal was to force feedback or engagement. This was achieved by heavy advertising and promoting some of the Facebook page content.

The promotion was enhanced by creating a Facebook event where subscribers could publish and vote for the product that would eventually be designed and manufactured. The list of potential products was comprised of suggested products that were posted or "liked" by the subscribers.

3.3 Wednesday: Product Design

At this stage of the one week challenge, the project was quite established and our followers were steadily increasing over both of the social media platforms. The final product was chosen so that the design for the product could be generated.

The demo model was printed on a 3D printer provided by the Industrial Department's RPD lab. The first printed product was a rough printed product to enable further investigations on finishing and quality.

3.4 Thursday: Manufacturing and Quality

The final product is manufactured on the same 3D printer only using an improved design and tolerance for a higher quality product. The timeline for the delivery of the product is the next day therefore using knowledge gained from manufacturing the previous demo model, the final product could be manufactured in time.

3.5 Friday: Package, deliver and social media feedback

The final day of the one week challenge was to deliver the product after some paint was added to the now successfully 3D printed product. This hype (on Social Media) peak was reached with a succession of posts and some reposts of previous highly attractive posts to get the target group involved and excited for the revealing of the actual product.

4 RESULTS OF THE CASE STUDY

The final product, a Baymax paperweight modelled from Disney's movie Big Hero 6, is shown in Figure 6, was delivered to the Industrial Department's secretary. The product had the most votes and thus created the most hype and it served its purpose where it would be used daily by the secretary to create order on her desk.

Figure 6 - The community selected, open designed, co-manufactured product

The results of the one week challenge Facebook page will be discussed in the following categories: Post Reach, People Engaged by Gender and Age, and People Engaged by Location. All the data was accumulated and presented in the Facebook page administrative section.

4.1 Post Reach

Post Reach is the amount of people that were able to view the posts surrounding the one week challenge. Figure 7 represents Post Reach as divided along two types namely Self-Reach and Advertised-Reach. Self-Reach is the amount of people who viewed posts from the one week challenge Facebook page and/or got in contact with the content through friends commenting, liking or sharing the content. Advertised-Reach occurs when you promote a page or posts via Facebook, which significantly improved one's reach. Over the course of the week, two posts were promoted to compare their reach and test the varying effectiveness of graphic and video posts.

The Self-Reach was directly relatable to the amount of posts that were posted on the one week challenge Facebook page and was mostly aligned with the same amount of people that was currently subscribed to the page. Although the Self-Reach wasn't as substantial as the Advertised-Reach, it serves as a better indication of how much contact the project had with the industrial cluster.

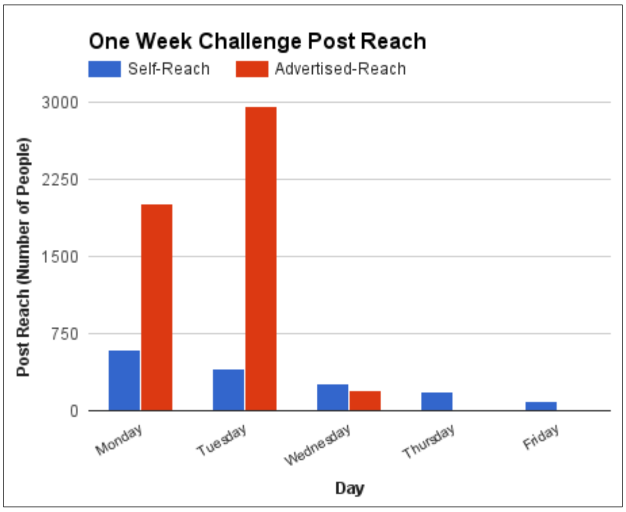

Figure 7 - Post Reach illustrating the number of people reached during the challenge

The Advertised-Reach has two major points of interest. The first day, an investment of seventy rand over the course of one day for a graphic explaining the one week challenge and just over two thousand people that made contact with this post. The second day a promotion of a video for the same amount and duration was done. The expectation was to receive a much higher contact reach, but only received just more than three thousand contacts. This indicated that although videos were commonly accepted to be better at getting information across, it still only reached the same amount of contact compared to a simple graphic that had the same information on it.

4.2 People Engaged by Gender and Age

As can be seen in Figure 8, more female subscribers engaged with the posts made in the one week challenge Facebook page than men. This may be due to our product being for a female secretary and therefore relates more to women.

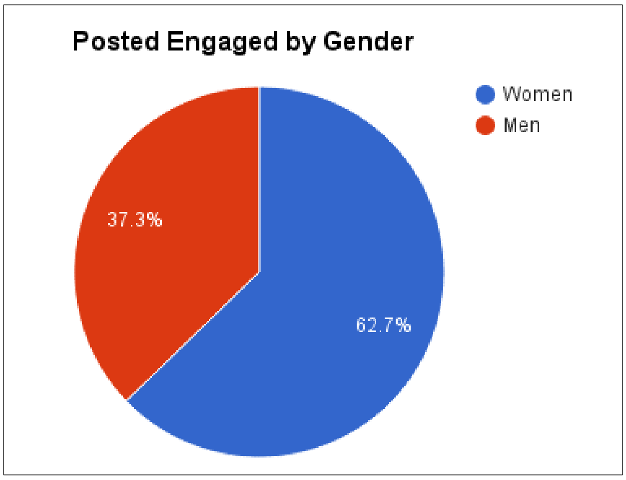

Figure 8 - People Engaged by gender during the challenge

Figure 9 shows the age distribution chart of the people that engaged on the Facebook page. The one week challenge successfully achieved majority engagement in the age groups between eighteen and twenty four by a combined total of just over forty percent. If the age bracket between eighteen and thirty-four is totalled then the combined engagement is two thirds of the total engagement. This reinforces the fact that we reached our desired industrial cluster of young adults.

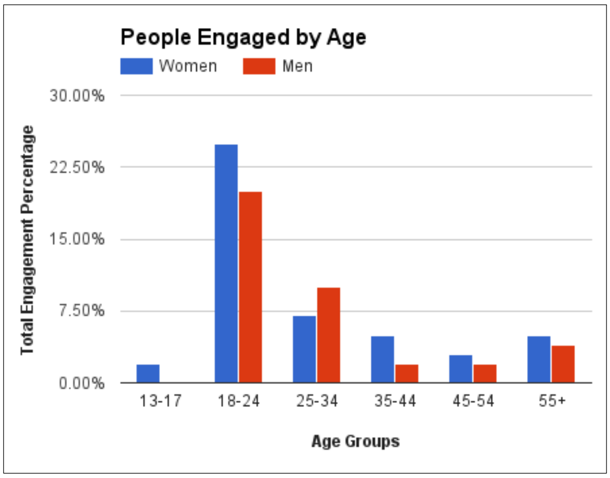

Figure 9 - People Engaged by age during the challenge

4.3 People Engaged by Location

The focus area, industrial cluster, consisted of Industrial Engineering students of the University of Stellenbosch, and by examining the pie chart in Figure 10, it is clear Stellenbosch had the most people that engaged on the one week challenge Facebook page. Furthermore, if you combine Stellenbosch's number of engagement with that of Cape Town and Paarl (which are two towns in close proximity of Stellenbosch), then the engagement by location comprises of more than three quarters of the total engagement. Both these above-mentioned facts thus prove that we succeeded in reaching our desired industrial cluster.

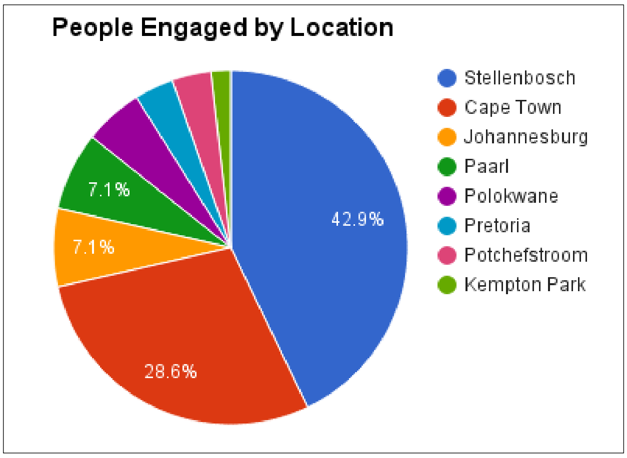

Figure 10 - People engaged by location during the challenge

The results show that when you compare a simple social manufacturing project to a traditional manufacturing project, the amount of customer engagement is higher. More superior designs could be achieved faster when social media is incorporated. In total fifty-eight people engaged in this one week challenge where, for instance compared to a traditional project, only a handful of people would engage on customer data and specifications and it might take up to month to achieve the same output.

5 CONCLUSION

The business model elements of social manufacturing are explored and discussed. Compared to traditional design processes the research and conceptual design phases become shorter in social manufacturing. The case study provided valuable data with regards to crowd sourcing. This case study also proved that a product can be designed, manufactured and delivered within a week using social manufacturing methodologies. These experimental results illustrated the business benefits of taking the intellectual property issues out of the product development equation.

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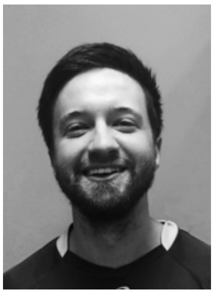

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