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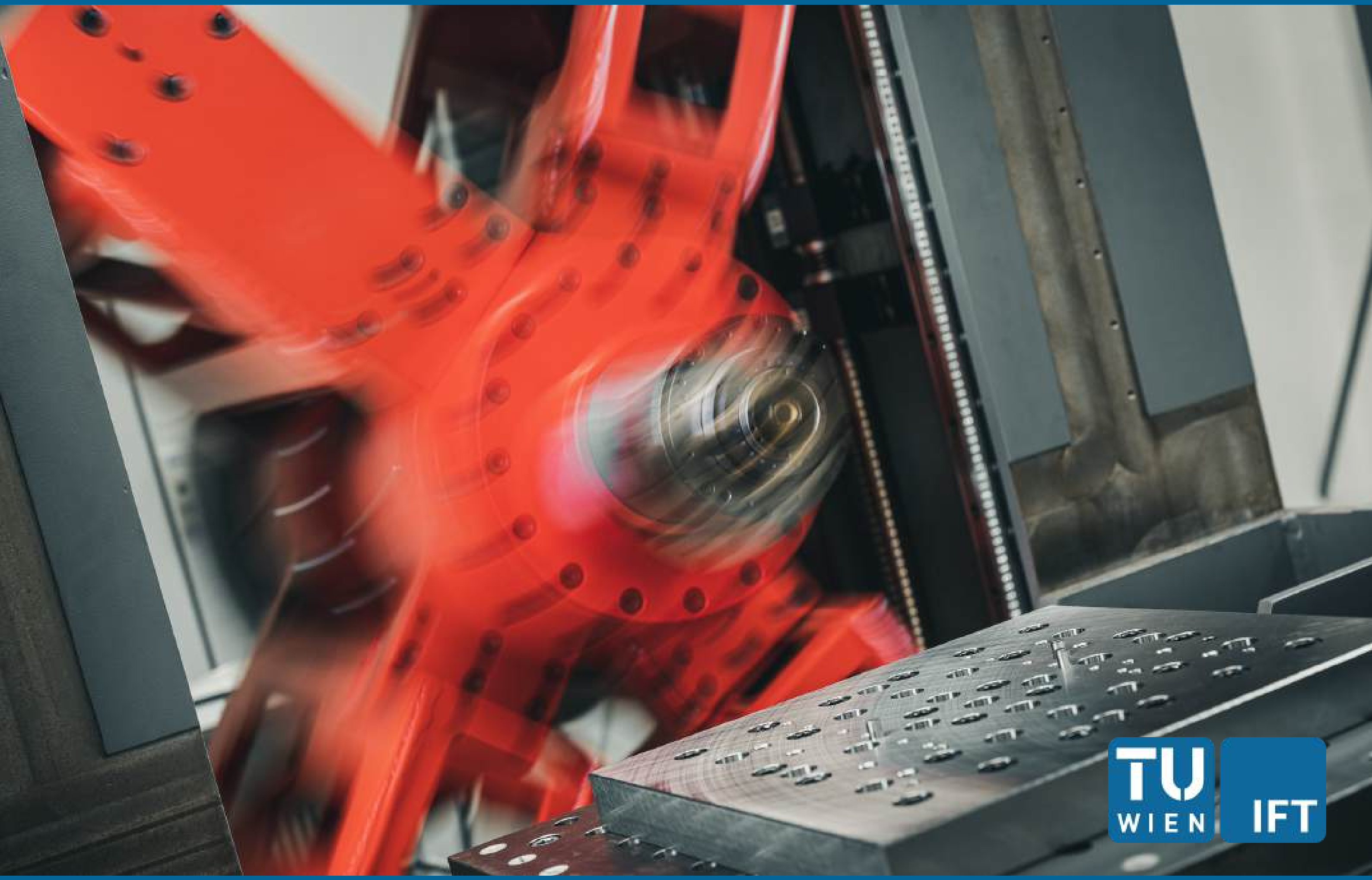
TWIN TRANSITION IN MANUFACTURING

Wiener Produktionstechnik Kongress 2024

Band 6



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Univ.Prof. Dipl.-Ing. Dr.techn. Friedrich Bleicher (Hg.)
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The editorial team would like to thank all contributors for their invaluable input, and we hope that this book provides meaningful insights into the field of **Twin Transition in Manufacturing.**

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We extend our gratitude to **Mariia Kostrova, Gernot Pöchgraber, Markus Prießnitz**, and the entire team at the Institute of Production Engineering and Photonic Technologies for their invaluable support throughout the development of this publication.

CONTENTS

6. WIENER PRODUKTIONSTECHNIK KONGRESS
Twin Transition in Manufacturing

Preface

Dear Readers, esteemed Attendees of the Vienna Production Congress,

It is my great pleasure to welcome you to the Wiener Produktionstechnik Kongress 2024 (WPK2024), an event that brings together distinguished experts from both industry and academia to explore and discuss the significant developments shaping the future of manufacturing. This year's congress is particularly vital and of current importance, as it focuses on the Twin Transition in Manufacturing - the simultaneous shift towards green and digital production paradigm - that will transform the way goods are produced across Europe and the world.

Europe has long been home to a robust manufacturing sector that has played a central role in driving the continent's economic development. Particularly in Central European economies, manufacturing remains a key value-adding branch, providing jobs, fostering innovation, and contributing substantially to GDP. However, the manufacturing sector is now facing new challenges in a rapidly evolving global landscape. With markets becoming increasingly volatile and unpredictable, companies must adapt quickly to stay competitive. Simultaneously, the pressing issue of climate change demands a fundamental rethink of how industries operate, with the European Commission's ambitious "Green Deal" setting the stage for a climate-neutral society by 2050.

This dual pressure - climate imperatives and market volatility - highlights the critical role manufacturing must play in ensuring both economic resilience and environmental sustainability. The transition to greener production methods, which emphasizes energy efficiency, resource conservation, and lower emissions, is not just a regulatory requirement but a necessary strategic shift. Equally, integrating advanced digital technologies into manufacturing processes is essential for increasing operational efficiency, enhancing flexibility, and reducing costs. This twin transition toward a green and digital economy is no longer a future vision; it is a present reality that is reshaping global value chains and redefining competitive advantage.

At the heart of this transformation lies the European manufacturing sector, which must lead by example, adopting sustainable practices while leveraging cutting-edge technologies to maintain its position in the global market. The ability to trace and verify green supply chains will become a critical differentiator, as customers and regulators increasingly demand transparency regarding the environmental footprint of products. Manufacturing companies must now adhere to strict green and digital standards to remain active players in global value chains, and this shift presents both challenges and opportunities.

The WPK2024 congress provides an actual survey and a discussion platform for addressing these challenges. With the theme of "Twin Transition in Manufacturing," the congress will showcase the latest enabling technologies, best practices, and innovative solutions that pave the way toward highly efficient, resilient, and sustainable production. Contributions from leading industry players, academic researchers, and policymakers will demonstrate how digital tools, such as sensor and actuator integration, model-based process optimization, digital twins, and artificial intelligence, can enable sustainable practices to create a future-ready manufacturing ecosystem.

In addition to technical advancements, the congress will emphasize the importance of workforce development in realizing the twin transition. As manufacturing processes become more complex and interconnected, reskilling and upskilling will be essential to equip workers with the knowledge and abilities needed for the digital and green economy. Lifelong learning will become a cornerstone of this new paradigm, enabling employees to stay agile and adaptable to ongoing technological advancements. The congress proceedings will highlight various educational initiatives and programs designed to foster this continuous learning environment.

The Wiener Produktionstechnik Kongress 2024 will also provide valuable opportunities for collaboration and networking. By bringing together thought leaders from diverse sectors, the congress will facilitate the exchange of ideas and best practices, promoting a shared vision for the future of manufacturing. This collaboration is critical, as the challenges of the twin transition are multifaceted and require coordinated efforts from all stakeholders. We are proud to present a program featuring contributions, whose insights in innovative topics will undoubtedly provide valuable guidance for navigating this transformative period.

The contributions of all the distinguished speakers, both from industry and academia, are captured in the WPK2024 Conference Proceedings. These contributions will serve as a comprehensive resource for attendees, providing a survey on the latest trends and advancements in sustainable and digital manufacturing. The proceedings will highlight the diversity of innovation that is driving the twin transition and are offering practical insights across various sectors.

I cordially invite you to engage fully with the discussions, presentations, and networking opportunities provided by the WPK2024 congress. Together with the organizational team, we are confident that the insights and innovations shared at this event will inspire and empower us all to drive the positive change in manufacturing industries and even beyond.

I look forward to welcoming you at the Wiener Produktionstechnik Kongress 2024!

Sincerely,

Univ. Prof. Dr. Friedrich BLEICHER

Head of the Institute of Production Engineering

and Photonic Technologies (IFT), TU Wien

Introduction

Twin Transition in Manufacturing explores the intersection of green and digital transitions within the manufacturing industry. This proceeding focuses on advancements in sustainability, digitalization, and innovation across various sectors in manufacturing.

Proceeding Overview

- **Machine Tools and Production Systems**

This section delves into innovations within the automotive industry, particularly focusing on the transformation towards electric vehicles and digitalization of production systems. It discusses how the company is leading the way in electromobility through significant investments in gigafactories and smart production systems. Additionally, advancements in industrial intelligence and digital twins in machine tools are presented, showcasing enhanced efficiency and sustainability through artificial intelligence, automation, and innovative control technologies.

- **Primary Shaping and Forming**

The focus here is on additive manufacturing, especially 3D sand printing for steel casting. This technique enables complex, lightweight designs that reduce material consumption and environmental impact. The chapter includes case studies in the mobility and automotive industries, demonstrating how bionic principles can optimize part design and reduce CO_2 emissions. Furthermore, data-driven approaches are emphasized for optimizing forming processes and improving the resource efficiency of metal forming techniques.

- **Machining**

This section explores the evolution of machining processes, particularly in sustainable aircraft production. It highlights advancements in simulation-based control systems for improving tool wear prediction and efficiency in machining processes. This section examines innovations like wire arc additive manufacturing and multi-axis machining, highlighting their ability to streamline processes. By integrating these technologies, manufacturers can significantly lower costs and boost productivity, especially in low-volume production runs. These advancements not only optimize material use but also enable greater flexibility and precision, making them ideal for producing complex, customized parts efficiently.

- **Data-Driven Manufacturing**

The final chapter focuses on how data ecosystems are enabling greener production methods. The shared use of data, as well as advancements like the digital product passport, are paving the way for more transparent and efficient manufacturing processes. This chapter showcases how discrete event simulations are pre-validated to optimize intralogistics systems, contributing to more sustainable and streamlined manufacturing operations.

These chapters collectively reflect the ongoing transformation in manufacturing, driven by a commitment to digitalization and environmental responsibility.

Keywords: Twin Transition, Digital Transformation, Machine Tools, Production Systems, Machining, Manufacturing

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European Manufacturing: Leading and Shaping Our Green and Digital Future

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Abstract

The manufacturing industry is a global base for prosperity and key to Europe's economic, social, and environmental sustainability, acting as the main driver of industrial innovation, job creation and growth for the European society.

The European manufacturing sector is currently undergoing green and digital transitions to become more sustainable, adopting circular economy principles to transform Europe into the first climate neutral continent by 2050. Going through these major transformations, the industry strives to retain leadership in a competitive global landscape, accelerating innovation and attracting investments.

On this journey, it is critical for European manufacturers to embrace digitalization to achieve leaner operations and boost profitability and competitiveness. The lack of workers with the right skills, however, is one of the biggest constraints to the successful green and digital transitions. It is therefore equally important to train the sector's workforce and develop their skills and competences to match the industry's current and future needs.

As a public-private partnership, co-funded by the European Union, EIT Manufacturing has a clear purpose to improve people's lives through sustainable manufacturing. This purpose is accompanied by the mission to connect manufacturing players by promoting talent and entrepreneurship to accelerate sustainable innovation in Europe.

During this presentation, CEO Caroline Viarouge will elaborate how EIT Manufacturing stimulates manufacturing ecosystems and supports European manufacturing companies, research institutions and universities with various instruments and activities, including talent reskilling and upskilling via educational programmes, as well as supporting startups through various calls, Access-to-Market and Access-to-Finance services, co-investment opportunities, and coaching and support in commercial expansion.

Keywords: Digitalization, circular economy, EIT manufacturing

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MACHINE TOOLS AND PRODUCTION SYSTEMS

"The best way to predict the future is to invent it."

— Alan Kay

WPK CONFERENCE PROCEEDINGS
6th Wiener Produktionstechnik Kongress, WPK 2024, Austria
Twin Transition in Manufacturing

Chapter: Machine Tools and Production Systems

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The Future of Automotive Production in Europe: Transformation and Challenges at SEAT S.A.

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Abstract

The automotive sector in Europe is facing the most challenging transformation and disruption in decades. The electrification of the vehicle portfolio, alongside the digitalization of manufacturing processes are key factors in this transformation. Identifying challenges and opportunities related to new technological trends, environmental sustainability, the demand of new markets and supply chain efficiencies is essential to maintain industrial competitiveness.

The Spanish car manufacturer SEAT S.A., with its two complementary brands SEAT and CUPRA, is undergoing the largest industrial, organizational, and cultural transformation in its 74-year history as it shifts from combustion to electric vehicles. Electrification is SEAT S.A.'s opportunity to lead the future. 70 years ago, SEAT put Spain on wheels and now the company is putting the country on electric wheels. With operations in over 70 countries and exporting more than 80% of its vehicles, SEAT S.A. is contributing to Spain's role as a major player in the automotive industry. The country is the second largest car manufacturer in Europe and the 8th biggest worldwide. The company's ambitious Future: Fast Forward project, in collaboration with the Volkswagen Group and PowerCo, aims to establish Spain as a European hub for electromobility through a €10 billion investment, which includes the electrification of its Martorell and Pamplona factories and the construction of Spain's first gigafactory.

SEAT, S.A. as part of the Volkswagen Group, one of the biggest automotive groups in Europe, is a clear example of how transformational challenges can be effectively addressed. The transformation of the company is affecting its three production centres: Martorell, El Prat de Llobregat and Barcelona. These are being transformed into the factory of the future with agile, networked, and optimized production and supply chains. This transformation is characterized by integrating advanced technologies, digitalization, data processing and improved logistics and a connected and agile supply chain to optimize production.

In the area of digitalization, artificial intelligence is increasingly becoming a key driver, making companies more productive, efficient, and sustainable. At SEAT S.A., it is utilized in areas such as supply chain optimization, predictive maintenance, quality control, and defect detection. An important aspect of the company's transition involves the upskilling the workforce to prepare them for the future through the most ambitious training plan in the company's history, encouraging a winning mentality and an openness to change.

The company works in guaranteeing the long-term sustainability of its business, which will be key in a highly competitive global market. Through the Volkswagen Group and its multi-brand strategy, SEAT S.A. shares resources to implement Smart Production across all its facilities, positioning the company in pole position to lead electromobility across Europe.

Keywords: Automotive Industry, Europe, SEAT SA, Electric Vehicles, Sustainability, Technological Innovation, Industry Challenges

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Industrial Intelligence - Improving Efficiency and Sustainability in Manufacturing

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Abstract

Sustainability imperatives call for fresh approaches to modern machine design. Selecting optimal motion and automation solutions is multifaceted, with no one-size-fits-all answer. Standard pneumatics, electrical automation, and controlled pneumatics each have trade-offs, whereas CO2 emissions and cost play roles. Guidelines are essential. Leveraging intelligent algorithms and artificial intelligence can reduce CO2 footprints. As an outlook we touch on emerging fields like biotechnology, which demand scalable automation solutions.

Keywords: Sustainability, Automation Technology, Pneumatics, Biotechnology, Energy Efficiency

1 Introduction

Sustainability aspects necessitate a novel approach to modern machine concepts. Selecting the optimal technological solution for motion and automation tasks is multifaceted, and making general assumptions is challenging. Therefore, guidelines are essential. Leveraging intelligent algorithms and artificial intelligence can significantly enhance existing technology in terms of reducing its CO2 footprint.

Furthermore, emerging application fields such as biotechnology are gaining prominence. Automation technology plays a pivotal role in scaling these applications.

2 Standard Pneumatic, Electrical Automation, and Controlled Pneumatics

Within modern machine concepts, various technological options exist for motion within the machine. These options include standard pneumatics, electrical automation, and controlled pneumatics (i.e., pneumatics supported by proportional valves). Each option has distinct advantages and disadvantages. As a rule of thumb:

- **Pneumatic**: Well-suited for shorter stroke lengths, stronger holding force, and longer holding periods.
- **Electrical automation**: Ideal for longer stroke lengths, weaker holding force, and shorter holding periods.
- **Controlled pneumatics**: Represents a compromise between these two technologies.

However, other factors, such as CO2 emissions and cost (both initial and total ownership costs), also play a role. Thus, no overarching assumption can be made regarding the superiority of one technology over another. In our discussion, we will provide decision support and highlight the respective sweet spots for each technology.

3 Sustainability and Efficiency in Pneumatics

Improving CO2 emissions and efficiency in pneumatic systems is achievable. Physics offers a solution: in specific scenarios, expansion energy alone can propel a pneumatic cylinder to its end position without requiring full pressure. This approach can save up to 60% of consumed air and enhance cycle times by nearly 25%. Leveraging

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intelligent algorithms and artificial intelligence within the programmable logic controller (PLC) is essential to achieve these savings.

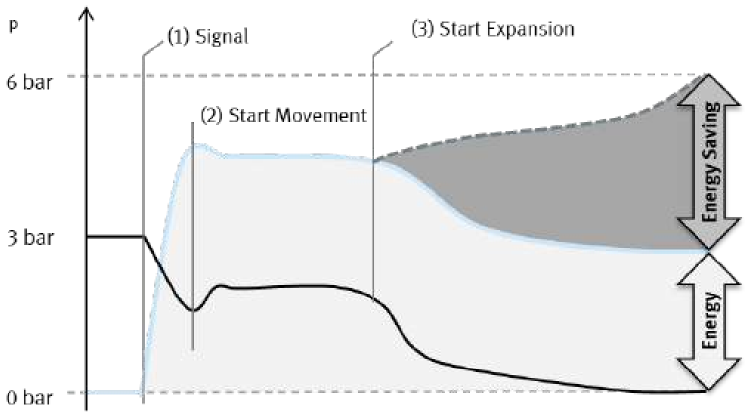

Figure 1: Smart Switching of a Pneumatic Actuator.

Figure 1 illustrates the principle of smart and energy-efficient switching for a pneumatic actuator. The process begins with the PLC sending a signal (1) to open the valve and initiate the air flow. Shortly after (2), the pneumatic actuator starts moving. An AI model, trained specifically for this purpose, identifies the optimal moment (3) when the expansion energy is sufficient to bring the actuator to its end position. At this point, the AI model locks the valve, ensuring efficient operation of the actuator.

4 Outlook – Biotechnology and Biomechatronics

The convergence of technology and biology represents one of today's most significant innovations. Numerous applications in pharmaceuticals, food processing, and personalized medicine drive the need for automation technology. Bioreactors play a crucial role in producing medicine, alternative proteins, and personalized meat, highlighting the demand for automation.

There are two current trends for bioreactors: large-scale reactors and small-scale reactors. Large-scale reactors are utilized in pharmaceuticals, green chemistry, alternative proteins and meat products, as well as in reducing CO2-footprint. Automation potential can be seen in areas such as gas control (N2, O2, CO2), air mass flow controllers, valve manifolds, and shut off valves. Industry 4.0 is also employed to control and optimize continuous processes in large-scale reactors.

On the other hand, small-scale reactors are used in personalized medicine, regenerative medicine, immunotherapy, and tissue engineering. Technologies like mass flow controllers, valve manifolds, pump technology, and cell counting technology are implemented in these systems.

Furthermore, there is a growing trend of completely integrated high throughput systems with multi-parallel bioreactors. These systems also include liquid handling to increase the quantity of production.

Lastly, emerging job profiles like biomechatronics combine automation, information technology, and biology, creating new opportunities in this field.

WPK CONFERENCE PROCEEDINGS
6th Wiener Produktionstechnik Kongress, WPK 2024, Austria
Twin Transition in Manufacturing

Chapter: Machine Tools and Production Systems

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Controller Integrated Digital Twin – A Boost for Dynamics and Accuracy in Machine Tools and Robots

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Abstract

Digital Twins have gained prominence in various applications, including virtual commissioning and process optimization. However, their use in real-time control systems is relatively new. In this article, we explore an innovative approach where the Digital Twin describes dynamic features of both machine tools and robots, as already implemented in Sinumerik ONE. Two distinct approaches are presented. First, we delve into the SINUMERIK function called Engineered Motion Control (EMC) that uses the Digital Twin to improve the dynamic and productivity of a machine. Next, we address robot modeling. Unlike machines, robot dynamics significantly depend on the pose and requires a more complex model than maps those variations.

Keywords: Robotic, Sinumerik, Model-Based Command

1 Introduction

Well known use cases of Digital Twins cover aspects like virtual commissioning before the physical machine does exist or optimizing the cutting process for production. Using a Digital Twin in real time control systems is rather new. This article provides a first insight into an approach where the Digital Twin describes dynamic features of a machine tool or robot as it is already implemented in Sinumerik ONE. The usage of dynamic models inside NC control systems implies an efficient approach for model generation as well as a good fit to the reality. Two approaches will be presented in this paper.

2 Optimized Dynamic and Productivity

In a first step the SINUMERIK function Engineered Motion Control (EMC) will be outlined.

2.1 Functionality of EMC

The approach is based on a Digital Twin describing a controlled dynamic machine model (Figure 1). The model is used to calculate feedforward control signals that compensate oscillations and cross talk effects affecting the workpiece quality at the tool center point.

The model used for the control is time invariant and consists in a transfer function system mapping the natural frequencies identified from the real machine. A semi-automatic modeling is possible based on frequency responses and the commissioning module Auto Servo Tuning from Sinumerik One. For easiness of implementation, the model is implemented directly as a discrete model [1]. A state control is applied [2]. The strategy for the pole placement aims at maximizing the bandwidth of the system without exiting eigenmodes.

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2.2 Benefits of EMC

The control algorithm for the dynamic machine model makes use of the model knowledge and allows to generate optimized outputs. With EMC, the jerk and acceleration can be increased without exiting natural frequencies or increasing quasi-statical deformation of the structure. A productivity gain of more than 10 % is usually reached e.g. for finishing operations of milling machines. Moreover, the bandwidth is increase and the contour deviation is reduced by more than 50% for typical milling operations.

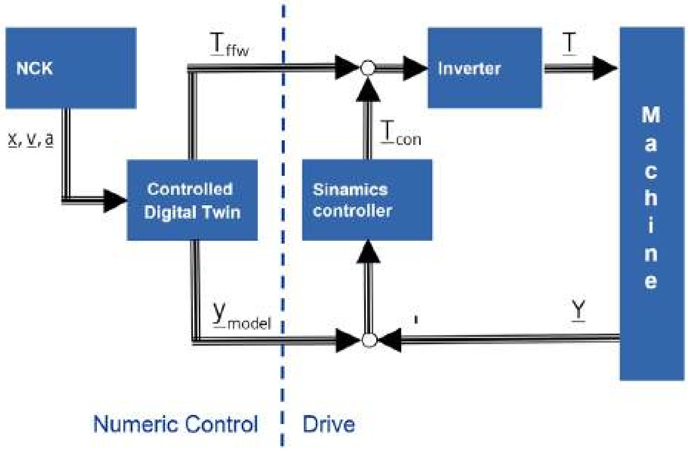

Figure 1: Engineered Motion Control. The feedforward control signals of the motor torques (Tffw) and encoder values (y_{model}) are calculated from the controlled Digital Twin.

3 Time Variant Model Extension for Robot

A model-based approach for robots needs to consider that the dynamics strongly depends on the pose. Eigenfrequencies, load inertias for each feed drive and compliance at the tool center point vary significantly over the working space. The Digital Twin within Sinumerik Run MyCC ROCO maps the nonlinear behavior of the robot.

3.1 Modelling approach

The modeling approach is illustrated in figure 2. The model is described physically and consists of lumped masses connected with spring / damper elements. The drive trains are abstracted. This simple description enables the control to evaluate the model in real time [3].

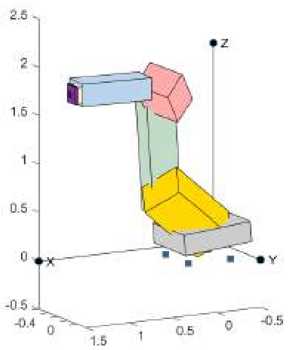

Figure 2: Sketch of a robot model as it is evaluated with Sinumerik Run MYCC ROCO for the whole working area.

3.2 Benefits of this approach

This model-based approach allows to increase the static accuracy of a robot in the workspace up to the range of the repeat accuracy. It also harmonizes significantly the performances of the robot and reduces the dependency between quality of the product and location within the workspace.

As shown on Figure 3, the path accuracy of a robot can be more than doubled with the compensation of cross talk and intalk effects.

Overall, using such a Digital Twin inside the NCK of Sinumerik brings robots much closer to the accuracy of machine tools what is a precondition to use the robot's flexibility also for demanding machining operations.

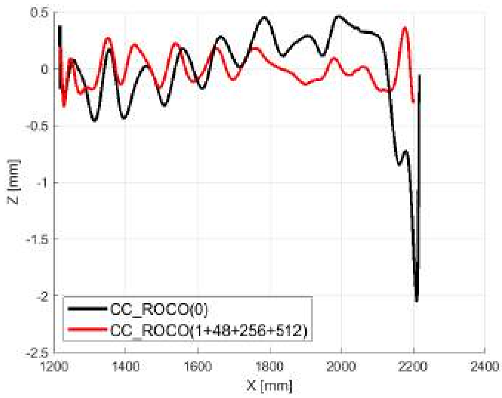

Figure 3: Path at TCP (measured with laser tracker) during a dynamic displacement. The black trajectory is without ROCO, whereas the red trajectory is with crosstalk and intalk-compensation.

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Innovative CNC Technology for Sustainable and Highly Efficient Manufacturing

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1 Extended Abstract

Analyses of metal-cutting processes have shown that the auxiliary components in the machine tool or its environment play a dominant role in the energy balance [1]. The power consumption of a CNC control including infeed and spindle motors usually comprises only 25 to 30% of the total input power required to operate the machine [1]. Most of the electrical energy is required to supply the auxiliary components for processing cooling lubricants, for supplying compressed air and hydraulics and for cooling of feed and spindle motors [2] [3]. A study on the energy consumption of machine tools has underlined that machines consume in standby more than 50% of the energy that is required in cutting operation [1].

In general, the efficiency of CNC power electronics is very high [2]. Based on the latest generation of power semiconductors and new control algorithm, HEIDENHAIN's generation 3 power electronics has even improved the energy balance of the control cabinet. However, a major step on the road map of carbon footprint reduction based on further efficiency improvements of the CNC electronics seems to be unrealistic. In contrast, a proper management of pumps, cooling aggregates and a reduction of the compressed air consumption promise significant energy savings [2] [3]. Consequently, HEIDENHAIN's new linear absolute position feedback systems for machine tools will no longer require compressed air during operation. A new innovative scanning technology and a new sealing concept allow proper and reliable operation without the need of compressed air.

Figure 1 shows the average input power of three different machine types which are specified in table 1, [1]. The results point out, that a high level of automation for 24/7 operation of machine tools has significant impact on the energy consumption. As parts and fixtures need to be cleaned to 100% to avoid clamping errors caused by remaining chips in the machine workspace, the energy consumption to process the cooling liquid increases significantly [1] [3]. However, automation allows significant higher throughput, and the energy consumption per part might decrease in comparison with non-automated machines.

Table 1: Machine tool concepts considered in a study on energy consumption during standby and productive operation [1].

Characteristics	Machine 1	Machine 2	Machine 3
Workpiece flow	manual	Pallet changer	Part magazine
Operation	1 shift/d	3 shift/d	3 shift/d
Redundant cutting tools	No	yes	Yes

This presentation focusses on the potential of organizational measures and manufacturing control approaches to scale down the carbon footprint of parts being produced with machine tools. Figure 1 clearly outlines the significant power consumption in standby, that is dominated by components to provide compressed air, properly tempered cooling liquid and further auxiliary components. Switching off the auxiliary components in standby

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would significantly improve the energy balance but lead to a transient state in the thermal equilibrium of the machine and to corresponding accuracy problems of the machine tool.

To optimize the carbon footprint of machine tools under operation and parts to be produced with them, manufacturing control needs to assure that:

1. standby operation and nonproductive time in general is minimized or – if possible - completely avoided,
2. the metal removal rate is maximized regarding the thermal load capacity of cutting tools and the mechanical load capacity of tools, fixtures and machine.

Three different manufacturing control principles provided by modern CNC technology and digitalization concepts are considered in this presentation (figure 2 and 3):

1. Feedforward control based perfectly validated NC programs.
2. Feedback process control based on local process intelligence provided by the CNC.
3. Feedback process control involving the manufacturing team.

The feedforward control approach covers the idea of controlling all machine operations required for a steady and error free part production by a perfectly defined process input (figure 3, left). In manufacturing, the NC code as the relevant input to control the machine operation needs to be validated to 100% with respect to programming errors, that generate collisions and tool overload and – as a consequence - unexpected downtime. HEIDENHAIN's latest control generation TNC7 offers outstanding simulation performance to monitor collisions between machine components, fixtures and tools. Combined with the software option Dynamic Collision Monitoring in the second generation, the risk of unexpected downtime and useless energy consumption in standby due to collisions can be reduced close to zero. The manufacturing job can be validated on the NC code level with a programming station enhanced to a digital twin of the real machine (figure 4).

A new cutting data calculator provided by HEIDENHAIN's TNC offers outstanding performance to operate the cutting tools at their thermal and mechanical load limit in a highly process reliable mode. Based on a TNC-integrated digitalization of material data and HEIDENHAIN's next level of trochoidal milling offered with Optimized Contour Milling (OCM), the energy consumption per part can be reduced up to 67% (figure 5 and 6). The load control on the cutting tools avoids nonproductive time and waste parts caused by tool breakage. As a result, HEIDENHAIN's approach to operate the cutting tools at their thermal and mechanical load limit offers significant potential to reduce the carbon footprint per part in the sense of feedforward process control.

With the feedforward process control approach errors cannot be totally avoided. As an example, raw material characteristics might vary locally and tools or the machine might be damaged (figure 7). Consequently, the machine will produce waste parts or will stop unexpectedly. To reduce the carbon footprint, process errors need to be identified and feed back to the process control algorithm of the CNC (figure 3, middle). HEIDENHAIN's numerical controls provide local process intelligence to monitor machine and tool overload and offer a bundle of powerful measures to automatically keep the machine in productive mode in case of process errors. The new software option Process Monitoring significantly reduce the reaction time in case of tool breakage. Process Monitoring identifies process irregularities and stops the manufacturing job immediately. Figure 8 shows the impact of an unexpected nonproductive time due to tool breakage. The reaction time of the shop floor staff will lead to useless energy consumption of the machine, whereas the software option Process Monitoring manages to recognize the error and to get the machine into productive operation with very short reaction time. By that, impacts of tool breakage on the carbon footprint per part can be controlled down to a minimum.

If the machining process needs to be aborted because of process errors, the machine might be back in productive operation after the next workpiece is in the machine. Nevertheless, process errors need to be analyzed by the shop floor team to finish the corresponding manufacturing job successfully. Digitalization can provide detailed diagnosis information on process errors, like the corresponding NC line and spindle load in case of a tool breakage or warning and error messages of the CNC control. Monitoring services like the HEIDENHAIN StateMonitor will inform the shop floor team via messenger services on process irregularities. A detailed bundle of relevant information is attached to the process irregularity. The shop floor team can close the loop efficiently and restart the manufacturing job with a well mapped-out set of corrected process parameters (figure 3, right). In this way, digitalization significantly contributes to a fast and reactive manufacturing control loop closed efficiently by the shop floor team.

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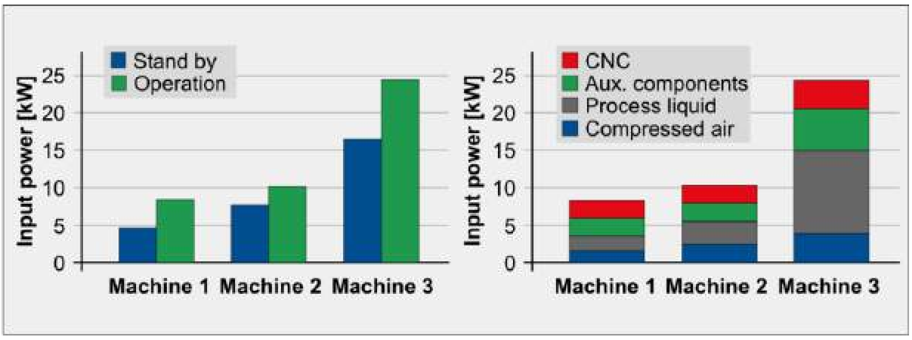

Figure 1: Average input power of three different machine tool concepts during standby and cutting operation [1].

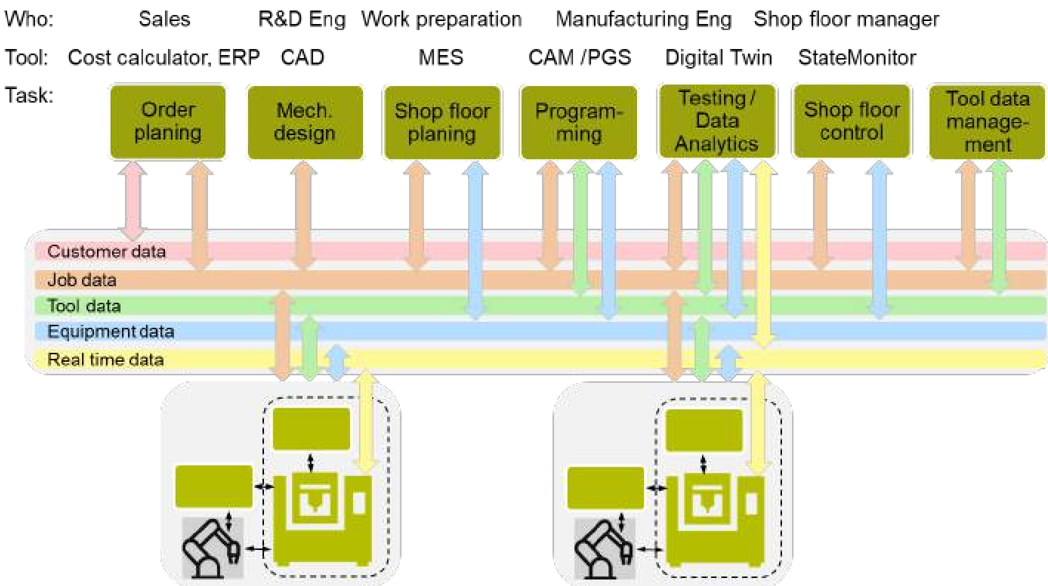

Figure 2: Manufacturing job processing and digitalization

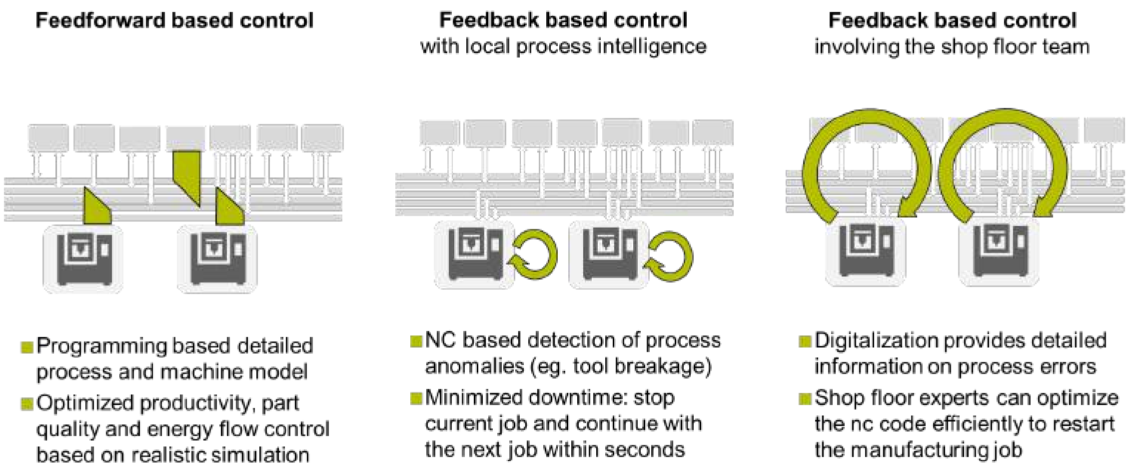

Figure 3: Feedforward and feedback-based process control

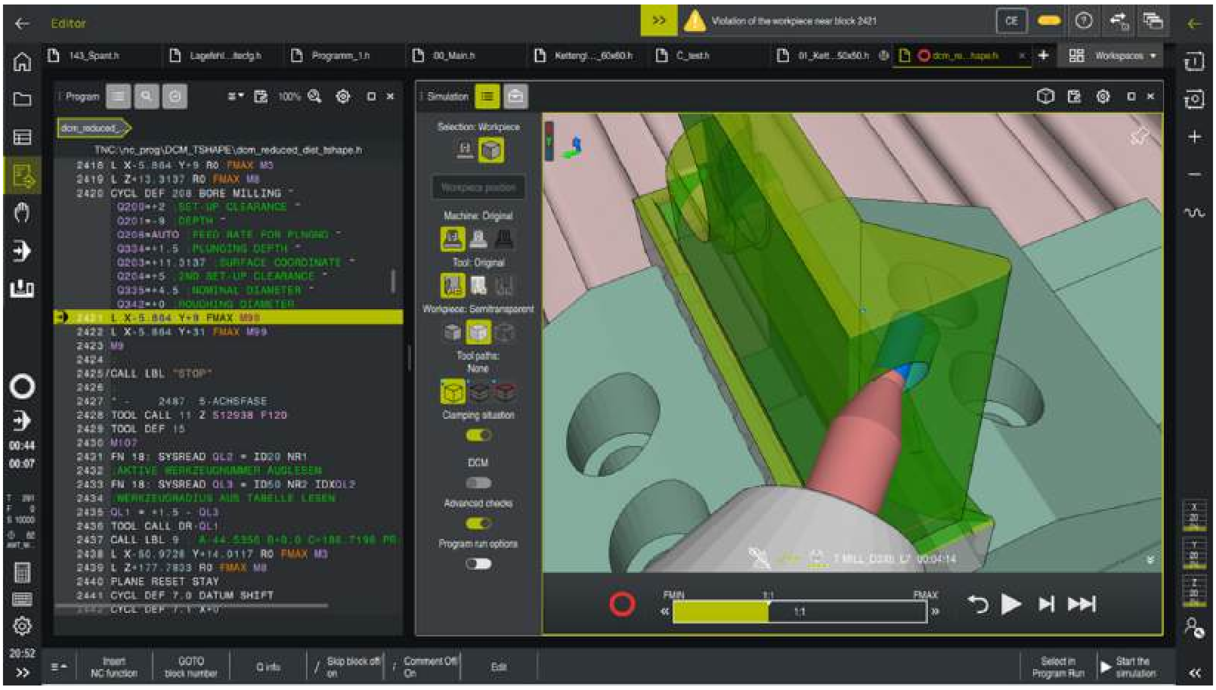

Figure 4: Advanced precheck of the manufacturing job with NC code based 3D simulation including tooling and fixtures of machining setup

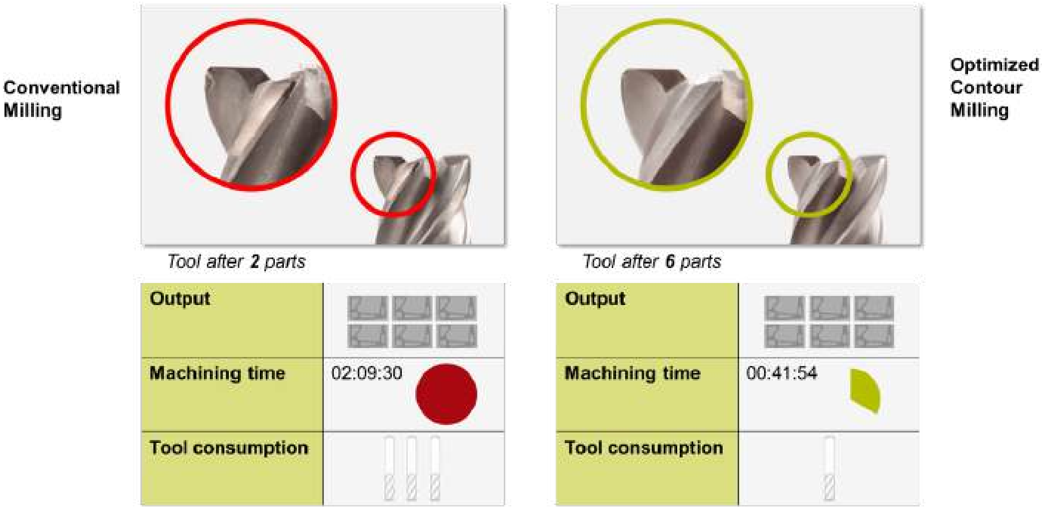

Figure 5: Comparison of conventional milling and Optimized Contour Milling - the next generation of trochoidal milling. Tool lifetime can be exceeded 3 times and machining time is reduced by factor 3.

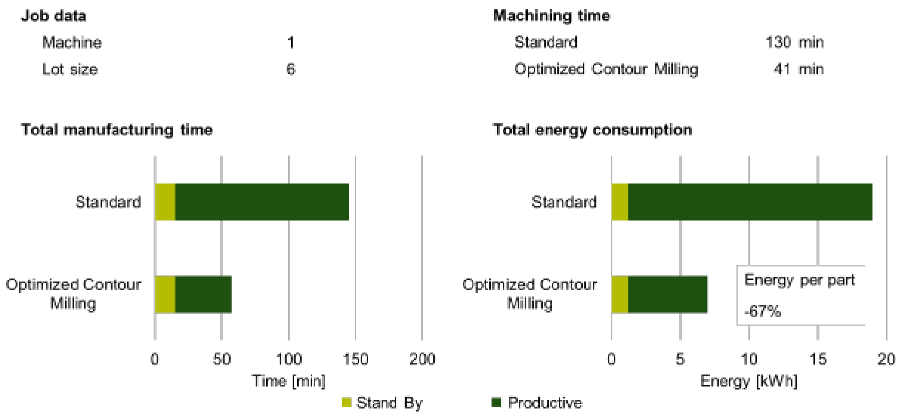

Figure 6: Productivity improvement and reduced energy consumption by optimized cutting parameter and tool path based on the cutting tests shown in figure 5.

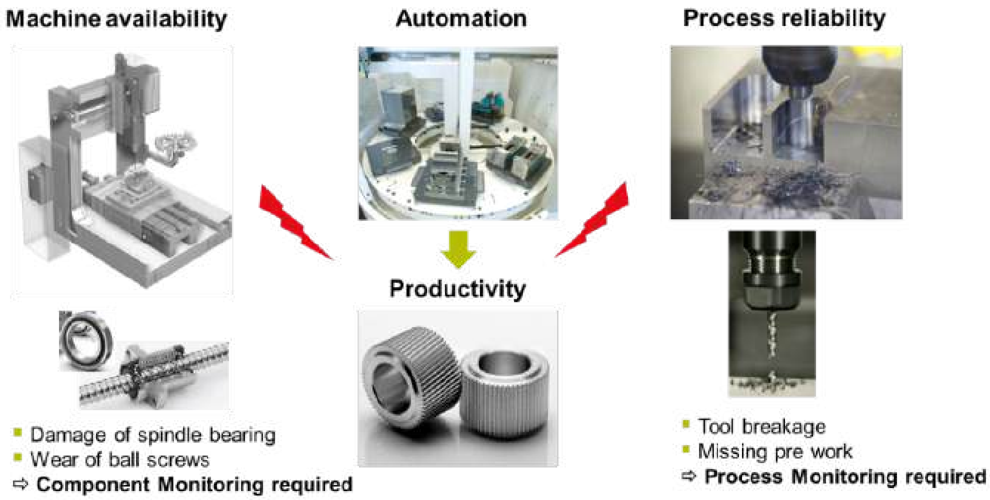

Figure 7: Enhance productivity by automation and local process intelligence on the CNC level to avoid machine down time caused by component overload and process errors.

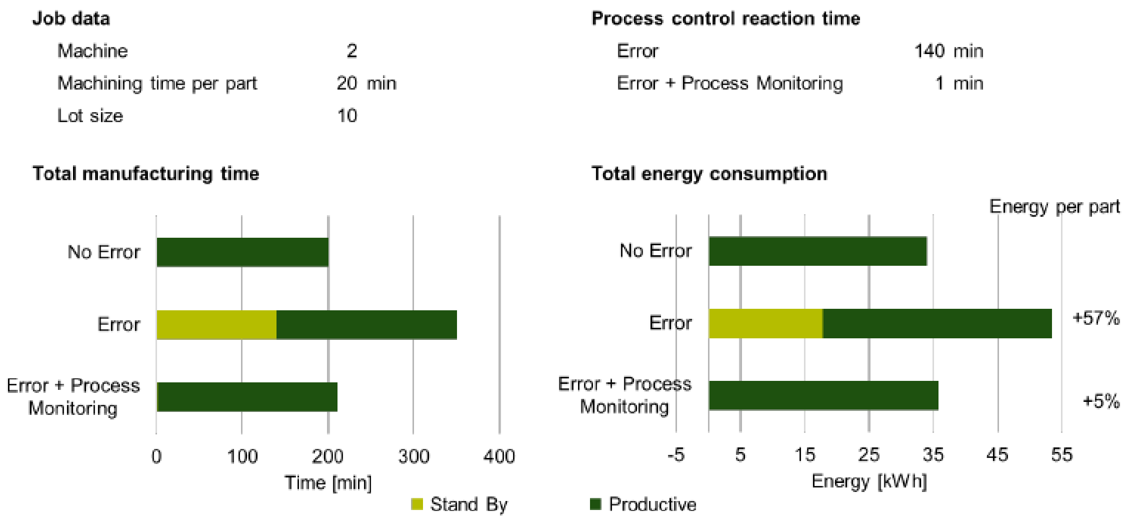

Figure 8: Case study on the impact of tool breakage in automated manufacturing on productivity and energy consumption with and without process monitoring.
Machine 2 refers to the characteristics in Table 1 and Figure 1.

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A Study on Industrial Tool Wear: Assessing the Potential for Optimised Lifespan Utilisation of Indexable Inserts Through Automated Wear Detection

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Abstract

This research focuses on the development of an autonomous wear detection system for indexable inserts used in manufacturing processes, with the goal of optimising tool life. The study addresses the challenge of premature tool replacement in an industrial setting, where tool lifespan is often underutilised. A prototype machine vision system was designed and tested, incorporating an 8.9 MP monochrome camera, macro lens, and deep learning software to measure flank wear. The system was validated against high-precision microscopy, revealing an average deviation of 27.4 µm. Analysis of 676 cutting edges of indexable inserts from an Austrian machine manufacturer confirmed that many inserts were retired with significant remaining lifespan, suggesting that tools are frequently replaced after only 50-60% of their potential use. The study highlights the viability of integrating such systems into industrial environments, with potential economic and environmental benefits. Future work will focus on improving measurement accuracy and expanding the dataset to further validate the hypothesis across different manufacturers and industries.

Keywords: Indexable Inserts, Tool Life Optimisation, Wear Monitoring, Machine Vision, Deep Learning

1 Introduction

In manufacturing, the shaping of materials into products is typically achieved through conventional machining techniques, including turning, milling, and drilling. These techniques rely on the use of sharp cutting tools. Indexable inserts are commonly used in these processes due to their cost-effectiveness and versatility across various operations [1]. Tool wear is a phenomenon that occurs and develops during machining processes [2]. It has a considerable impact on the efficiency of machining processes. If not monitored, it can result in a deterioration of cutting performance and surface quality, leading to an increase in downtime and costs. It has been indicated that tool failures are responsible for unscheduled machine stoppages and 15-40% of the costs of produced goods [3]. To address tool wear, Tool Condition Monitoring (TCM) strategies are essential for extending the lifespan of cutting tools [2].

Although indirect methods are commonly employed, they often lack the precision required to determine crucial wear parameters, such as flank wear. Direct measurement techniques are more accurate than indirect methods but require manual inspection, which interrupts the machining process [4]. Consequently, there is growing interest in machine vision (MV) systems for wear detection. These systems use cameras and software to autonomously detect and analyse tool wear, offering the potential for seamless integration into machining equipment. This study explores the development of a prototype MV system designed to autonomously detect wear on indexable inserts, assessing its viability for real-world machining applications.

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2 Problem Statement and Objective

Indexable inserts undergo wear and must eventually be replaced. While the replacement timing can be precisely aligned with the end of the lifespan in serial manufacturers producing the same products, this alignment is more challenging for machining companies who constantly produce different products or variants. Aside from research test setups, there is currently no precise optical in-situ method available for accurately monitoring tool wear. The interim removal of the inserts for measurement and potential reinsertion is not economically viable [5]. Therefore, often the only reference left is to estimate the end of the lifespan based on the traversed paths, the tool's engagement time or periodic replacement of the inserts [6]. Surveys conducted by the authors among European manufacturers (2024) reveal that tool replacement is often based solely on the operator's intuition and experience, resulting in a conservative approach to prevent breakage. This practice is prevalent across several European manufacturing companies, as confirmed by these surveys conducted on the shop floor.

Although numerous scientific papers have demonstrated that wear can be detected and quantified using optical methods and machine learning, and that it is possible to integrate image processing systems into machines, these solutions currently exist only in research environments and not in industry [7, 8, 9]. The actual question of what potential is lost because the inserts are replaced prematurely is still open. This work was written to explore this topic. The hypothesis is that the inserts are replaced at about 50-60% of their lifespan. The objective of this work is to confirm or refute this hypothesis.

3 Research Gaps

This study addresses the issue of determining the potential for optimising the lifespan utilisation of indexable inserts among European machine manufacturers. As previously mentioned, experts in both academia and industry, including manufacturing experts and machine operators who were surveyed during preliminary work, as well as several scientific papers, suggest that the lifespan of indexable inserts is often utilised up to only 50%. However, there is a notable lack of literature quantifying the actual potential that remains untapped in this area [5, 10].

Extensive literature exists on optimising tool lifespan for specific processes and material-tool pairings. Moreover, numerous studies have successfully demonstrated the integration of sensors, such as optical MV sensors, into machinery [11]. Nevertheless, there is a lack of research focused on the large-scale collection and analysis of used and discarded indexable inserts from multiple industrial enterprises to estimate the lost potential.

This research aims to fill this gap by providing a comprehensive assessment of the untapped potential in the lifespan utilisation of indexable inserts across various industries. This paper will serve as a kick-off for further investigations into this issue.

4 Methodology

This study focused on testing the hypothesis that the machining industry does not fully utilise the lifespan of their indexable inserts. To investigate this, a MV system was developed to monitor and evaluate tool wear. The goal was to analyse a large number of inserts from a leading Austrian machine manufacturer, specifically focusing on his two most commonly used types of indexable inserts

Data collection involved analysing 676 edges of inserts, with a subset validated using a high-precision microscope. The results provided initial insights into the potential underutilisation of tool life, confirming that this approach is a promising starting point for further studies. While the prototype demonstrated sufficient accuracy, future improvements in hardware and software were identified to enhance precision further. This research serves as an initial step toward more comprehensive studies on tool lifespan optimisation.

5 Experimental Setup and Data Collection

An industrial partner supplied indexable inserts that had been discarded after use in real machine conditions. These inserts were sourced from carbide scrap, and therefore, no specific information about the machining processes is available. The provided inserts include the 'CNMM120412-R4' type, used in turning operations, and the 'ODMT0605ZZN-D57' type, used in milling operations.

The ‘CNMM120412-R4’ inserts, produced by Seco Tools GmbH, are made from the TP2501 material, which is primarily designed for machining steel but is also suitable for stainless steel and cast iron [12]. The ‘ODMT0605ZZN-D57’ inserts, manufactured by Walter Austria GmbH, are composed of WSP45S with a

TiAlN+Al2O3+(Al) coating, making them suitable for both steel and stainless-steel applications [13]. It is important to note, that TP2501 and WSP45S are manufacturer-specific carbide grades.

The remaining tool life of these inserts is estimated. As stated in the ISO 3685 standard, the average flank wear width VB, and the maximum flank wear width VB_{max} can be measured to determine the wear condition [1]. For this reason, a stationary MV prototype has been developed where the inserts are manually inserted, an image of the flank face is taken, and VB is measured automatically. A total of 676 cutting edges are analysed and compared with the specified thresholds (as outlined in Table 2) to determine the remaining tool life. This prototype should be able to be integrated into the machining area or turret at a later stage, so the design must ensure that the harsh environment doesn't damage the MV system.

6 Wear Detection System

For the sake of simplicity, this system has been designed as a stationary prototype, whereby the inserts are manually placed within a 3D printed mould. This allows for the precision and potential of the used inserts to be tested prior to the system being integrated into a machine. The prototype development consisted of two main parts: hardware and software.

6.1 Hardware Design

The prototype included an 8.9 MP monochrome CMOS camera, a 1,5x macro lens, a ring light for uniform illumination and a linear stage for precise positioning of the inserts. As the system is not built into the machine at this stage, the indexable inserts have to be manually positioned in front of the optical system. To ensure that the inserts are positioned within the depth of field of the lens, the inserts are placed in a 3D printed mould mounted on a linear stage, which allows accurate positioning. The system has been housed in a tube-shaped protective housing to ensure durability in harsh machining environments on future machine integration. Figure 1 illustrates the developed prototype.

6.2 Software Development

A MV program was developed with the objective of automatically classifying the wear state of indexable inserts. The program determines the maximum flank wear width VB_{max} and the average flank wear width VB from an image of the flank face. The fundamental functions of the program are as follows: image acquisition, identification of any breakage to the cutting edge, localisation of the cutting edge, calculation of the area of flank wear, and finally, measurement of VB_{max} and VB. The MV program was developed using the MV software Aurora Vision Studio, including their deep learning platform, Aurora Deep Learning. The deep learning model is based on a convolutional neural network (CNN) architecture. The pre-trained deep learning networks from Aurora Deep Learning were further trained with 100 labelled images of flank wear of the supplied inserts.

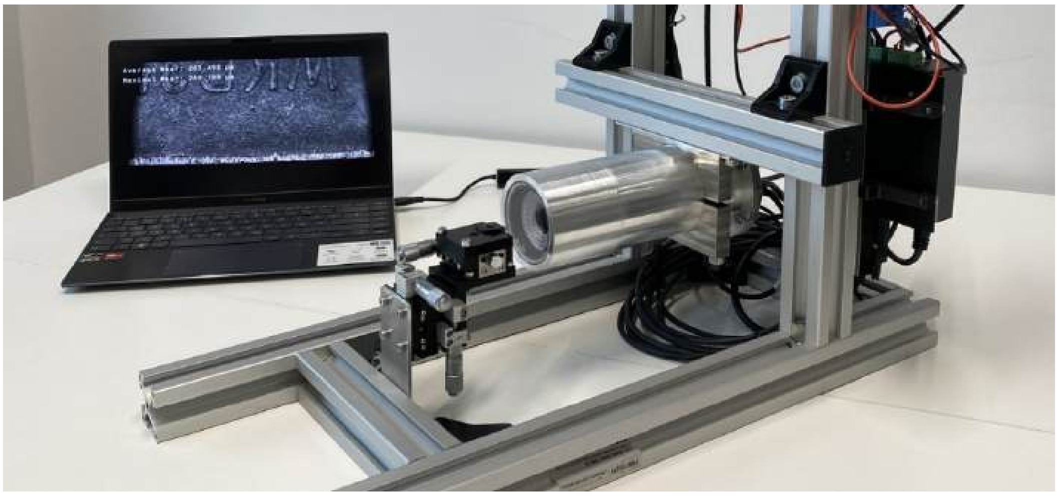

Figure 1: Prototype for flank face inspection

7 Results

A total of 676 flank faces of indexable inserts from an industrial partner, utilised in industrial machining, have been subjected to analysis.

The inserts were procured from the manufacturer's carbide scrap to closely replicate real-world conditions.

7.1 Validation of Prototype Accuracy

Given the considerable effort required to validate all inserts, only a small number were selected for microscopic measurement and validation. Eight inserts of the CNMM120412-R4 type and four inserts of the ODMT0605ZZN-D57 type were subjected to microscopic measurement. This resulted in 32 measured cutting edges for each insert type.

The InfiniteFocus G5 microscope from Alicona was used for validation purposes. However, the software provided is not suitable for measuring average wear, and therefore only VB_{max} was validated. A total of 64 cutting edges were validated, 32 of each insert, in order to validate that the same algorithm works equally well on both inserts. Table 1 displays the calculated deviation for both types of inserts.

Table 1: Deviation from the MV system

	Average deviation [µm]	**Median deviation** [µm]
ODMT0605ZZN-D57	26,6	20,9
CNMM120412-R4	28,4	18,1
All inserts	27,4	20,0

It is important to recognise the distinction between the mean and median deviation. The latter is influenced by the presence of flank wear patterns, which may not be consistently observed in all cases. Additionally, it is essential to acknowledge that the results of a microscopic measurement may vary if conducted by a different individual, particularly in terms of accurately determining the precise location of wear.

In consideration of the high flank wear thresholds identified in section 7.2, in comparison to the 27.4 µm deviation, the precision is deemed to be sufficiently accurate to estimate the potential for extended use of inserts.

7.2 Real Life Wear Assessment

The principal objective of this analysis is to evaluate the VB_{max} and VB of inserts utilised in industrial machining. In instances where the wear is uniform across the insert, the focus must be on evaluating the VB; however, in cases where the wear patterns are not uniform, the focus is on the VB_{max}. In particular, both maximum and average flank wear can determine whether the tool has reached the end of its life, with both values being compared against predefined thresholds [1].

Figure 2 illustrates the outcomes for both inserts. The results are presented in the form of bar graphs, which illustrate the number of indexable inserts for each of the seven categories. The first five categories represent equal intervals of the maximum permissible threshold for VB_{max} and VB. The values for these thresholds are presented in Table 2. The thresholds for CNMM120412-R4 turning inserts are based on the ISO 3685 standard. For ODMT0605ZZN-D57 milling inserts, the average wear threshold is based on the ISO 8688-1 standard, while the maximum wear threshold is based on the *Praxis der Zerspanungstechnik* textbook, which is more conservative than the ISO 8688-1 standard [14, 15, 16].

Table 2: Permissible flank wear thresholds

CNMM120412-R4	Threshold average wear	300 µm	[14]
	Threshold maximum wear	600 µm	[14]
ODMT0605ZZN-D57	Threshold average wear	350 µm	[15]
	Threshold maximum wear	700 µm	[16]

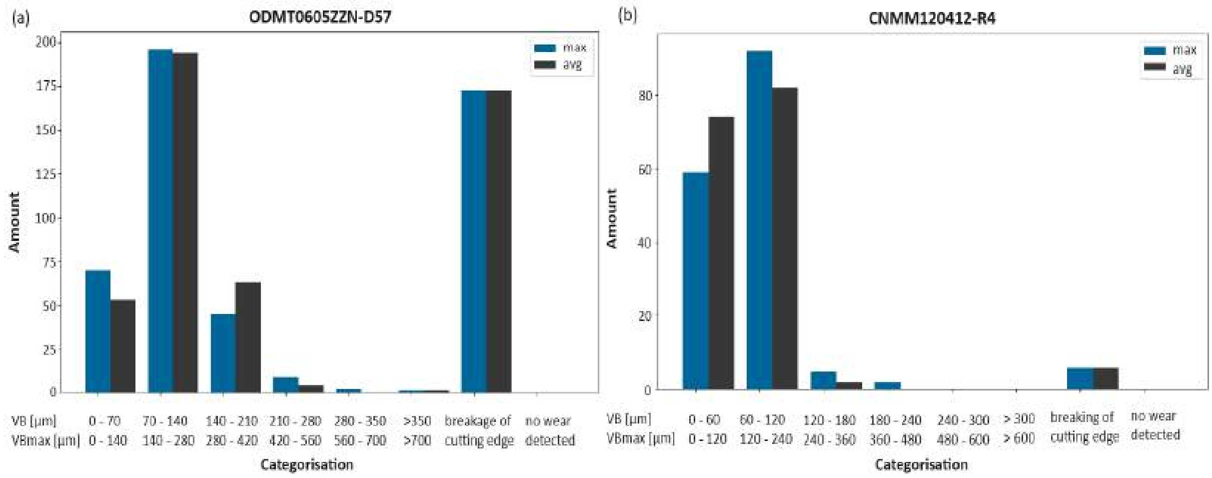

Figure 2: Flank wear analysis: (a): indexable insert type 'ODMT0605ZZN-D57'; (b): indexable insert type 'CNMM120412-R4'

8 Discussion

In this chapter, the findings of the study are critically evaluated, with particular attention to the interpretation of results, identification of limitations, and discussion of the broader implications. These considerations serve as a foundation for future research and potential practical applications

8.1 Interpretation of the Results:

The data presented in both graphs demonstrates that the majority of inserts are positioned within the first two bars, which indicates that the inserts listed there were utilised for a maximum of 40% of their tool life, suggesting that the theoretical potential of the inserts is not being fully utilised. However, stating that most of the inserts have reached only 40% of their anticipated tool life assumes a continuous linear increase in wear, which is not entirely accurate. The wear rate initially follows a degressive pattern (Phase I) due to high surface roughness peaks, and only later becomes linear (Phase II). Thus, if we assume, a linear increase from the beginning, as we do, the actual utilisation would be even less than 40%, reinforcing the point that there is considerable potential for extended use of the inserts [17].

A significant proportion of the 'ODMT0605ZZN-D57' inserts are classified as having a broken cutting edge. The reason for the discrepancy between the barely worn and broken cutting edges has yet to be determined. Potential causes for the high number of broken cutting edges include the use of inappropriate machining parameters or damage caused by rough handling during disposal. As the inserts are randomly selected from the carbide scrap, there is no information about the machining parameters, which limits the ability to investigate this further.

8.2 Identification of the Limitations of the Study

In order to ascertain the broader applicability of the observed potential in indexable inserts, it is recommended that inserts from a range of manufacturers be included in subsequent studies. It should also be noted that the threshold values stated in the existing literature are often quite general and may not be directly applicable to different machining conditions. Consequently, it is necessary to assess the suitability of these values for a wide range of machining parameters.

Additionally, the inserts were obtained from carbide scrap, and it is uncertain what damage might have occurred during disposal. This damage could include breakages or chipping of the inserts not caused by the normal production process but by rough handling afterwards. However, since the deep learning model identifies wear based on its distinctive appearance, it is unlikely that wear was measured incorrectly. The main concern is that some inserts may have been wrongly classified as catastrophic failures due to breakages or chipping that occurred after their actual use in machining. Future studies should aim to use inserts handled under controlled conditions to reduce these uncertainties.

8.3 Discussion of the Implications of the Results

A further validation of the results for these inserts would be facilitated by the reuse of some of the inserts that have already been tested. It is necessary to test these inserts for catastrophic failure, with careful documentation of the time to failure. This empirical approach will serve to validate the threshold values previously established in the literature. Subsequent research based on this work will involve the re-insertion of samples of the previously analysed inserts into the machine and their continued utilisation until they are no longer fit for purpose.

9 Conclusion

In the course of this study a prototype for the autonomous evaluation of wear on indexable inserts, with a particular focus on measuring flank wear in order to estimate remaining tool life was successfully developed. The principal findings indicate that the prototype exhibited an average deviation of 13% or 27.4 micrometres. Although there is scope for enhancement in the prototype's measurement precision, the current level of accuracy is considered sufficient for estimating the potential extended use of the indexable inserts. These findings have provided valuable initial insights into the lifespan of these tools.

9.1 Importance of the Results for Practice

The practical implications of these findings are of considerable significance. The prototype demonstrated that the two most commonly used indexable inserts at a machine manufacturer in Austria still had considerable potential to remain in use under real conditions. This provides substantial evidence to support the hypothesis that these inserts are frequently replaced prematurely. Although this study alone cannot yet confirm or refute the overall hypothesis, it provides a promising foundation for further investigation. The optimisation of indexable inserts has the potential to result in significant cost savings and an enhancement of production efficiency, thereby aligning with both economic and environmental sustainability goals.

9.2 Suggestions for Future Research and Further Development

It is recommended that future research focus on enhancing the precision of the prototype's measurement capabilities in order to provide a more reliable assessment of the tool wear.

Furthermore, to validate and expand upon the findings of this initial study, future work should involve the analysis of a larger number of inserts from a greater variety of manufacturers and industries. A larger dataset will help to confirm the hypothesis that in the machining industry, indexable inserts are being replaced too early.

This study represents an initial investigation that has already demonstrated the potential for extending the usage of indexable inserts. Further research, involving the re-insertion of these inserts under real-world condition is essential to deepen the understanding of tool wear and to ensure that the promising findings of this initial study can be applied across the industry.

10 Acknowledgments

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PRIMARY SHAPING AND FORMING

"The engineer has been, and is, a maker of history."

— James Kip Finch

3D Sand Printing for Steel Casting - A Game Changer

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Abstract

Additive Manufacturing (AM) has an increasing impact on modern fabrication processes. Especially in terms of tools, gauges and other consumables like grippers and fixtures, AM proofs to decrease costs and speeds up development processes. In addition to metal AM processes 3D sand printing (3DSP) fills the gap towards larger parts with several tons of weight for example tooling frames for presses. With the need of a reduction of the CO2 footprint of products and processes 3DSP allows to design more complex castings by using bionic principles. 3DSP enables more lightweight designs for castings than classical approaches, which leads to new ways of thinking tools and big parts for mobility applications. Especially in the transportation sector it opens new, cost-effective ways to manufacture big parts for trains and other heavy vehicles.

Keywords: 3D sand printing, indirect additive manufacturing, casting, rapid prototyping, bionic design

1 Introduction

Sand casting as a manual manufacturing process has been established to form objects out of metals for more than 5 millennia. It provides a wide range of dimensions, complexity, and designs. Future growth of this "old" industry requires the application of the latest advances in mold production to keep up with market needs and competing technologies.

The potentials of 3D printing or additive manufacturing (AM) in general for casting were identified early [1]. Alas, the application has been limited mainly to prototyping. 3D sand printing for the fabrication of molds for steel and metal casting is based on the binder jetting process [2]. The single steps of this process are based on the selective application of a liquid binder by an inkjet system to a thin layer of powder i.e., silica sand to print a complex geometry mold as seen in figure 1. This process enables a pattern free direct mold production directly from CAD models.

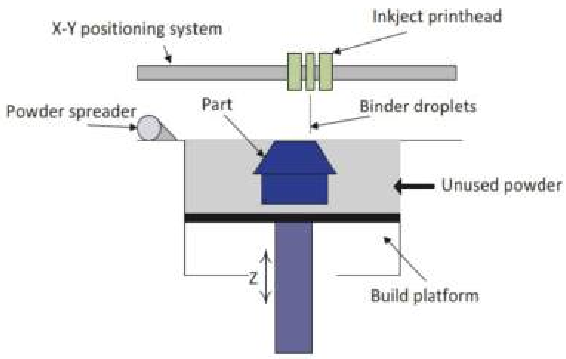

Figure 1: Principle of binder jetting according to [3]

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Often the term indirect additive manufacturing is used in this context, as the printed molds are used as tools for shaping i.e. pouring the final part. Through the integration of this technology in the existing casting lines in metal and steel foundries the following benefits for castings manufactured out of these printed molds are:

- Enabling a higher freedom of geometry [4-6]
- Possibility of new designs using bionic principles [4, 7]
- Lead time reduction through reduction or even substitution of process steps such as pattern making or machining [5, 8]
- Reduction of material consumption due reduction of weight [8-9]
- Better dimension control by reducing the number of molds and cores [5]
- Complex castings without tooling lead to a reduction of hard tooling requirements. [5, 8]
- Significant potential of reduction of CO_2 emissions compared to the traditional casting process due to design optimization and less material input and energy consumption [9]
- Reduction of the number of toxic consumables in sand mold manufacturing and environmental friendlier emissions compared to the conventional casting process [5]
- New opportunities for integrated sensors in molds [11-12]
- Cost reduction as a sum of all above

One of the main goals of this study was to apply bionic principles to develop more lightweight products by using casting technologies. Casting steel products in different sizes form a few kg to several tons by using printed molds and cores and even identify the possibility to combine it with other AM technologies is our main motivation.

2 Experimental methods

To prove the potential of bionic designs for existing parts out of steel casting, two representative examples are shown: one out of the mobility industry, a spare part for trains, the other one out of the automotive tooling industry, a bottom press housing.

2.1 Case Study Cargo Hinge

A cargo hinge is widely used a spare part in trains with a total weight of 635 g.

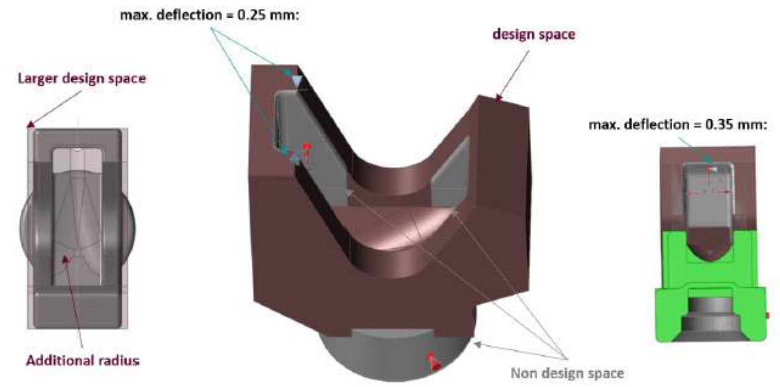

Figure 2: Boundary Conditions – Geometry & Material

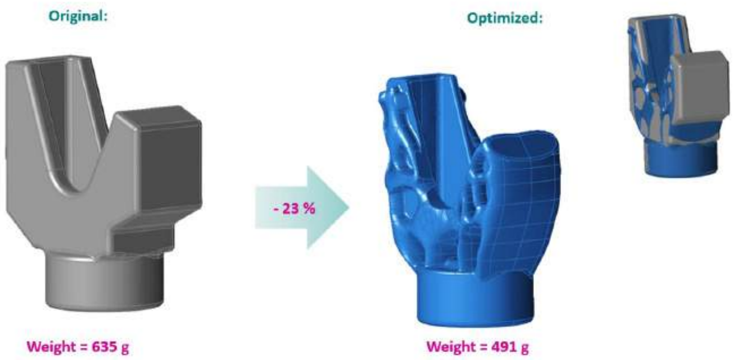

Figure 3: Topology optimization results

First boundary conditions were set for the original design. The design and non-design space was set to a max. deflection of 0.25 mm. In addition, three different load case scenarios, a setting material parameter to EN 1.6220, G20Mn5, E = 210 GPa, ρ = 7,8 g/cm³, ν = 0,3, Rp0,2 = 300 MPa, were defined for the simulations using a commercial software tool (Altair® Inspire™, 2020.1.1) for bionic design. The goal was to achieve a reduction of weight around 20% without losing any functionality.

Finally, before going into casting simulation, a full FE analysis for all stresses in all three load case scenarios was carried out (figure 4). All the load cases had to reach our goal of a deflection of less than 0.25 mm.

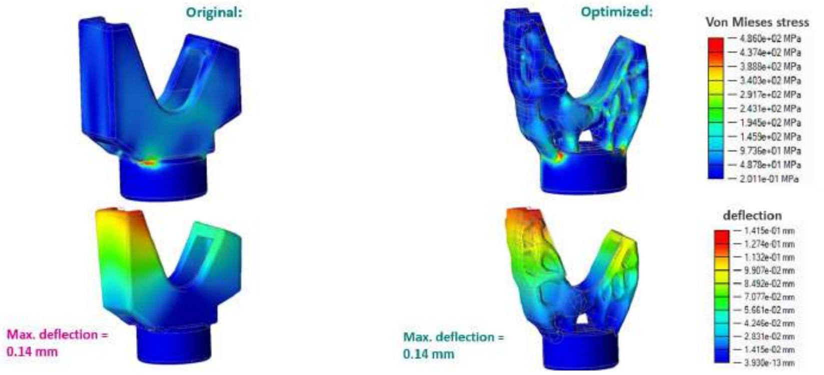

Figure 4: FE analysis for the three set load cases scenarios

After verification of the load cases the engineering of the printed mold started. The riser and gating system were calculated, using a commercially available casting simulation program (Altair® Inspire™ Cast, 2021.1.2). Further the behavior of the metal filling and solidification were simulated (figure 5).

The position and dimension of riser and gating system were optimized to avoid porosity and other shrinkage related defects in several iterative steps.

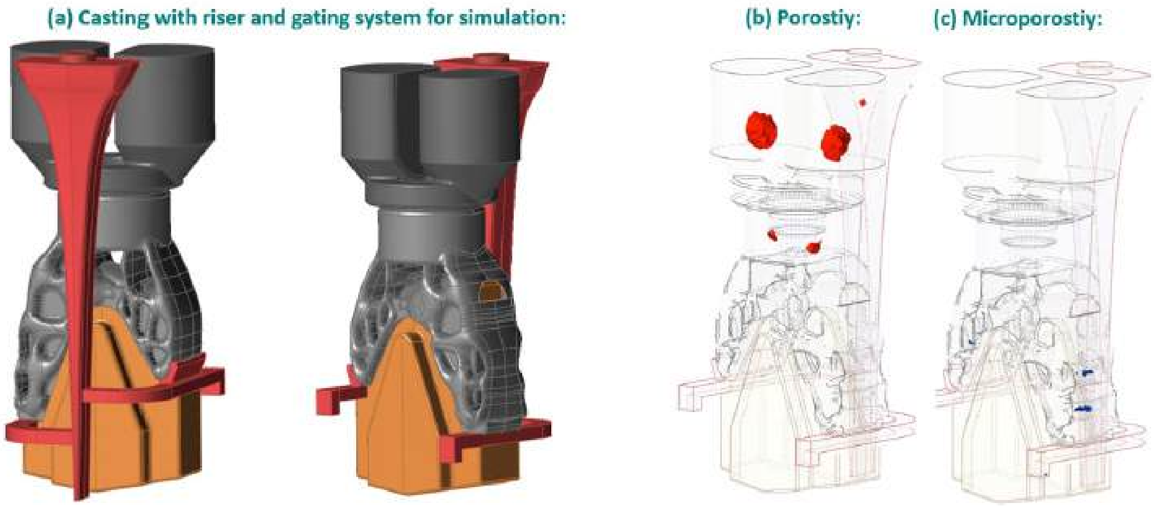

Figure 5: Casting with riser and gating system (a), solidification simulation for porosity (b) and microporosity (c) after end of solidification

The resulting file of the mold was transferred to a 3D sand printer via .stl-format and printed according principles described earlier. After cleaning the mold (3 parts) were assembled and prepared for pouring by a zirconia wash. Then the part was finally formed by pouring liquid metal with 1590 °C into the mold, shaking out the residual (sand) and a cleaning step. After this the part was heat treated (normalizing at 920 °C).

2.2 Case Study Bottom Housing

In automotive industries, time is of the essence in product development. This has been true for a long time, but in the last years the reduction of CO_2 during the manufacturing process gets more and more important. Using the same methods a bottom housing, made from EN 1.1118, G24Mn6, for a press in automotive industry was designed according to the principle of reduced stresses optimization for weight reduction.

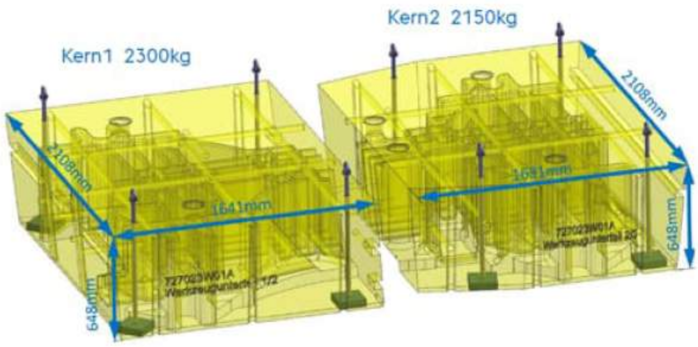

Figure 7: CAD file of bionic optimized sand mold for bottom housing

The final size of the bottom housing was 2.840 x 650 x 2.100 mm and 6.7 t in weight compared to the original part with 8 t.

3 Results

It was shown that a cargo hinge optimized with respect to bionic principles can be cast using 3DSP. Also the goal of a weight reduction of 20 %, without losing any functionality as seen in figure 8 has been reached.

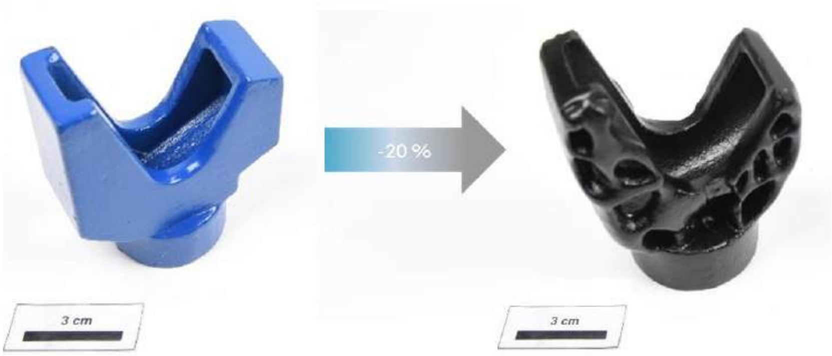

Figure 8: CAD file of bionic optimized mold for bottom housing

The results of the smaller casting part in this study could be upscaled to the finished bottom house casting. A reduction of approximately 15% of weight in comparison to the original used part could be achieved, too.

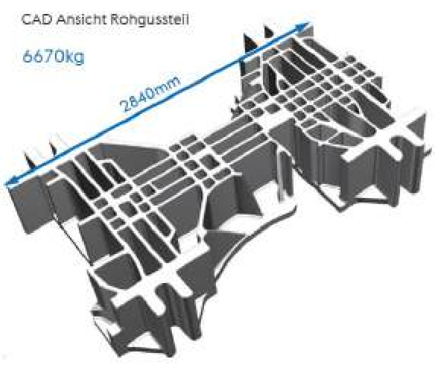

Figure 9: CAD file of bionic optimized mold for bottom housing

4 Summary

As shown above 3DSP has become an important, even disruptive tool in the steel casting industry. It´s main applications are for complex parts. It enables casts for small, complex, and heavy parts as well. It offers new design opportunities like bionic design and will even allow for multipart casts in metal. It provides a smart way to save weight and it lowers the CO_2 consumption during the production process through the option of near net shape casting and reduces manufacturing time.

5 Acknowledgements

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Data-Driven Process Optimization in Forming

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Keywords: metal forming, process optimization, data-driven models

1 Extended Abstract

Efforts towards interconnected and intelligent production are being promoted at national level in various initiatives, be it 'Industry 4.0' in Germany, 'Society 5.0' in Japan, 'Smart Manufacturing' in the US, 'Industry of the Future' in France, 'Made in China 2025' in China or 'Intelligent Factory' in Italy [1].

An essential component of all these endeavors is the data collected, for example from product design and process development, but especially from ongoing production. This database initially paints an incomplete and disruptive picture of reality in digital form. By curating and statistically analyzing the data, linking it with suitable models makes it possible to derive causal relationships that ultimately lead to decisions and actions. In this context, the term digital twins is used, which are utilized for a variety of tasks. Data-driven approaches are increasingly being used to build models that underlie digital twins, although there are still cross-domain and domain-specific challenges, particularly in the production context. The following aspects are typically major challenges, especially in metal forming [2]:

- Only small (or no) data available in early stages
- Different and incompatible data formats
- No possibilities for data reduction
- Closed-loop interaction between the virtual and real world

This contribution examines approaches and concepts that address the above-mentioned challenges from the perspective of metal forming. However, the proposed solution approaches might be also relevant for other manufacturing techniques, as pointed out in final paragraph.

Central to this is a reverse-engineering algorithm that reconstructs and transforms the geometric data into B-spline surfaces regardless of their origin, i.e. it enables, for example, discrete measurement data, simulation results and analytical design to be mapped in a compatible format [3]. In addition, this format of description enables enormous data reduction, which results in reduced memory requirements and faster data processing. Virtual data from simulations is used to enrich the measurement data or to be able to work at an early stage, for example to design robust and redundant sensor concepts for processes. This type of sensor concept design makes it possible to adapt the underlying simulation model through feedback in a standardized and efficient data format with real data acquisition in production operations [2].

To ensure the best possible quality of the numerical simulation data to be used in this way, a crucial step is its validation. For sheet metal forming this is especially relevant for the material description. The MUC-test is an experimental setup and evaluation routine for the rapid assessment of material models for sheet metal forming [4].

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In addition to metal forming, this methodology can be adapted to other manufacturing techniques and even process chains. For example, in series production of additive manufacturing, geometric deviation compensation methods from forming technology [5] could be successfully applied and enabled individualized process control from job to job [6]. In particular, the model-based differentiation between stochastic and deterministic deviations was the focus of interest.

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On Model Based Adaption of Deep Drawing Processes to Increase Process Stability and Resource Efficiency

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Abstract

In industrial deep drawing processes, stochastic fluctuations and disturbances in the manufacturing can result in a decreasing overall equipment effectiveness (OEE). The sensitivity to a fluctuation in component quality is further intensified in car body manufacturing due to complex geometries with small radii and the processing of high strength steels. The resistance to negative influences is referred to as resilience. This work presents and evaluates various smart stamping approaches that enhance the resilience of deep drawing processes. The focus is on the prediction of optimal press settings based on the incoming mechanical material properties. The mechanical material properties and component quality are continuously measured and fed into a model for analyzing the effects of fluctuations and disturbances on product quality through a feedback loop. Due to the ability to autonomously adapt to fluctuating environmental conditions and the automatic feedback, the meta model is considered as a digital twin.

Keywords: Sheet metal forming, Deep drawing, Process control, Sensorics

1 Introduction

In the European Union, nearly 13 million jobs are directly and indirectly dependent on the automotive industry [1]. To remain internationally competitive, there is immense cost pressure on production. In connection with the increasing importance of sustainable production, resource efficiency is gaining significance. High resource efficiency is advantageous in terms of overall equipment effectiveness (OEE) and CO_2 footprint. The OEE is a metric that measures the efficiency of production equipment by indicating the percentage of planned production time that is actually used to produce high-quality output [2]. Current challenges in the deep drawing of car body components include high geometric complexity, the processing of high strength steels for lightweight design, and the avoidance of lubricants for ecological reasons, which leads to reduced process stability. The lower the process stability, the more sensitive the reaction to stochastic variations in manufacturing conditions, such as incoming material properties, temperature, the continuity of a zinc coating on the blank and the resulting friction, or the positioning of the sheets in the tool. The more sensitive the reaction to stochastic variations, the more defects, such as splits, wrinkles, or springback, occur in the formed components. Smart stamping approaches can increase process stability in deep drawing [3]. This conference paper presents and evaluates various smart stamping approaches, with a focus on predicting optimal process settings based on the incoming mechanical material properties [4].

2 Smart stamping

Smart stamping approaches help increase the resilience of the deep drawing process. It is possible to classify them based on their degree of automation, see Figure 1. By means of a camera system, which evaluates the

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component quality after forming, scrap can be automatically sorted out so that no defective components are sent to the customer. In this approach, the complexity is comparatively low and no information about the cause of the defect is required. However, it should also be considered that this approach does not control or impact production but rather automates a 100 % quality control. This approach does not affect the OEE, but it can, at most, result in saving the labor costs for an employee performing quality control manually. Additionally, there are no known cause-effect relationships here, which means that the current process will not be improved, and there will also be no opportunity to draw conclusions for future manufacturing processes from process adjustments. This is the reason why it is more advantageous to adjust the press settings after each stroke for the next stroke, based on the resulting component quality, as elaborated in [5]. This system measures the material inflow at the flange. If a tolerance range is exceeded, the gap between the die and the blank holder is adjusted for the next stroke. In this context, it is referred to as production control rather than process control. The advantage, once again, is that no cause for the defect needs to be known. However, the challenge is that only fluctuations that follow a trend over many strokes can be compensated for. Individual or few outliers cannot be compensated for by such a system, which iteratively adjusts the gap between the die and the blank holder after each stroke.

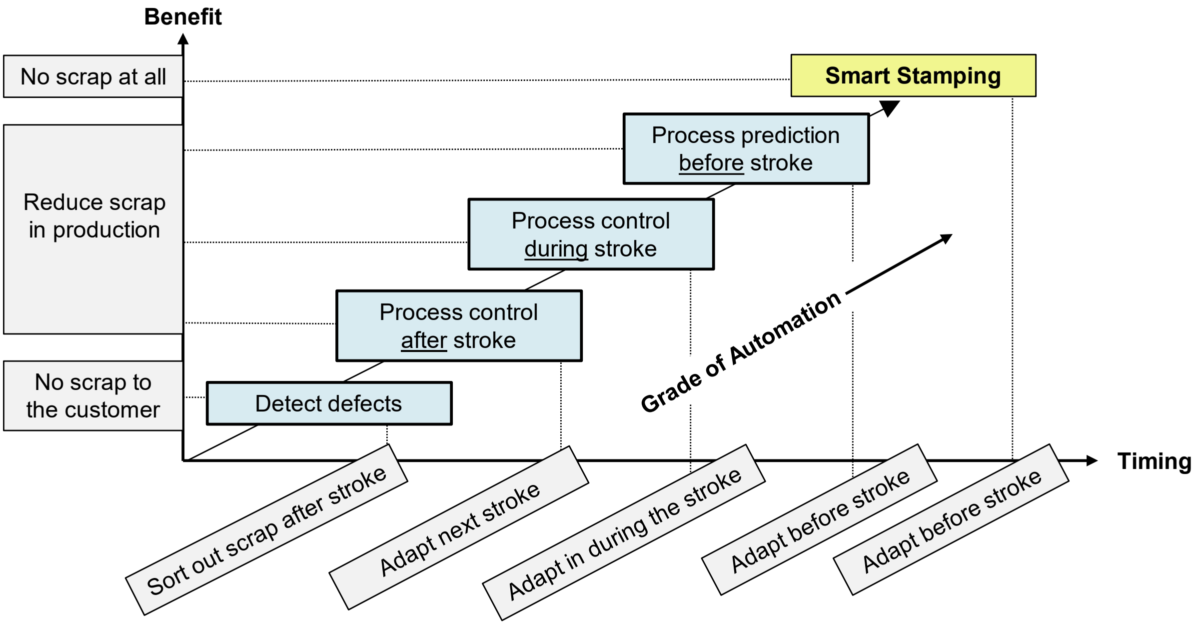

Figure 3: Smart stamping approach classified by grade of automation.

Another approach is to equip the tool with sensors, e.g. piezoelectric force sensors in the tool or material inflow sensors at the flange, which provide process data during the stroke [6]. Combined with a reference data set, defects can thus be avoided in real time and during the stroke. One way to control the material flow in real time is using actuators, which influence the surface pressure between the die, the blank, and the blank holder via a control loop. This approach avoids defects regardless of their cause for each stroke before they occur and therefore increases material efficiency even better than the two approaches presented before. In the context of real time control during the stroke, the data provided by the sensors during the stroke play an essential role, which is why the selection of the sensor, and its position are of particular importance. Studies on this can be found in [7]. One approach currently under research is the implementation of a holistic digital twin, including a feedback loop, so that not only the press settings but also the algorithm for predicting the optimal press settings adapt to changing environmental conditions. The approach presented below can be classified as an intermediate step between pure condition prediction and the long-term smart stamping vision. It includes nondestructive material testing systems and will be further discussed in the next chapter.

3 Predicting optimal press settings based on the incoming mechanical material properties

This smart stamping approach is based on preliminary investigations by [8] and [9], where the basic concept of predicting the optimal press settings before the stroke based on incoming material properties was introduced. What these approaches lack is the implementation of a holistic digital twin of the deep drawing process. This additionally includes a methodical approach to evaluate the sensors and their position, and a reliable and automated assessment of component quality based on these sensors. Furthermore, the system presented in this work includes two feedback loops. On one hand, the prediction of press settings based on the incoming material properties is correlated with the component quality, and thus, the prediction algorithm is updated every production lot. On the other hand, when leaving a defined tolerance range of the incoming material properties, the material card of the Finite Element (FE) simulation is adjusted. This way not only does the algorithm adjust the press settings, but the meta model itself also adapts to changing environmental conditions. A basic flow chart of this approach is shown in Figure 4.

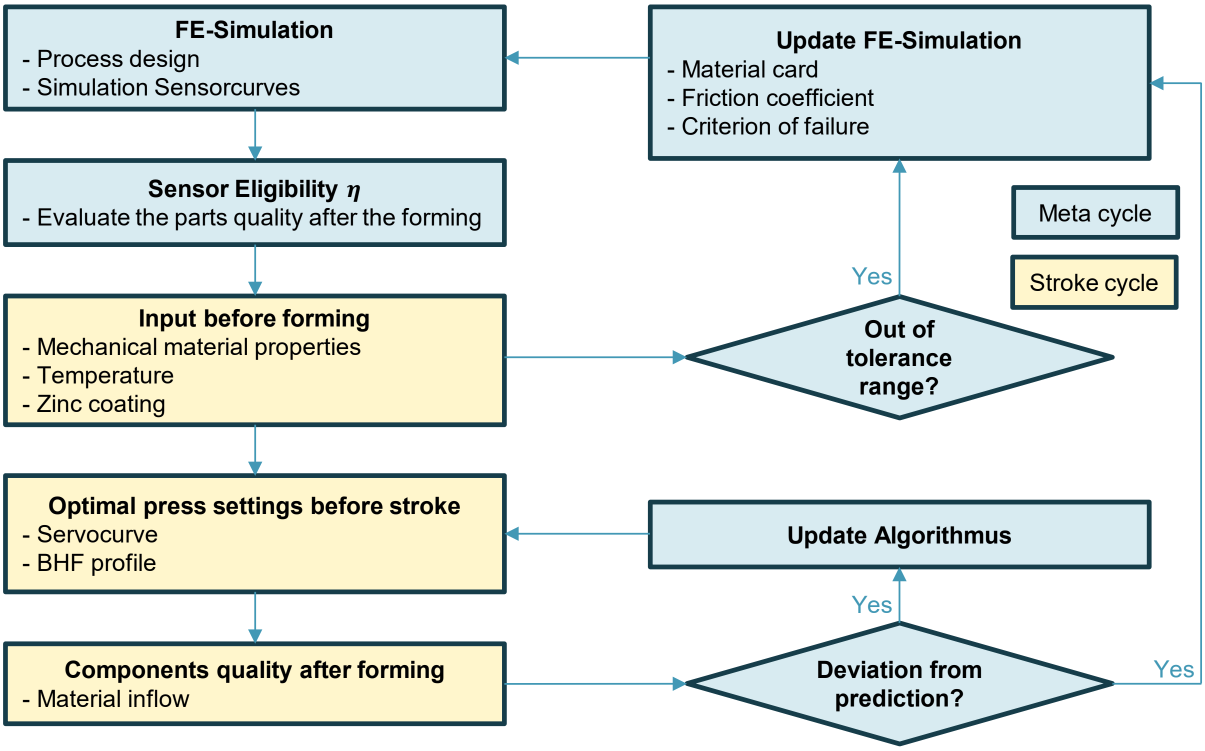

Figure 4: Flow chart for predicting the optimal process settings before the stroke.

The approach also distinguishes between the short stroke cycle, and the longer meta cycle. The stroke cycle corresponds to the duration of a full 360° rotation of the crankshaft in a mechanical eccentric press. This would correspond to a cycle time of 3 s for example, with a stroke rate of 15 strokes per minute (SPM). The meta cycle includes the feedback loops as well as preliminary investigations using digital tools such as FE simulations and sensor eligibility η [7]. It is not feasible to calculate this for each stroke new, but a suggested time span for the meta cycle could be one cycle per production lot or one cycle per month. The temporal differentiation between stroke and meta cycle in this approach is another differentiating feature compared to existing approaches. The limitations in predicting optimal process settings before the stroke arise when the accuracy of the FE simulation model is insufficient to reliably simulate the sensors, thereby making the calculation of eligibility η ineffective. Furthermore, predicting the optimal servo curve or the optimal blank holder force (BHF) profiles based on the mechanical properties of the incoming sheet is not effective if the calibration of the nondestructive material testing system is inadequate. The implementation of this described digital twin brings increased complexity but also offers advantages that the previously presented approaches do not bring. For example, the cause of defects is known and can be corrected, instead of just addressing the symptoms, i.e., the defects.

The approach presented in this chapter comes closest to the vision of Smart Stamping. In this vision, the quality data of the incoming coil are provided 100 % by the supplier and can be used by the forming company. The cut sheets are equipped with a QR code or a comparable tracking and tracing system, which also includes information about which coil they come from. A reference to the FE simulation and the material card of the FE simulation is also included in the tracking and tracing system. Any sensor data measured before, during, or after forming is automatically added to the database of the individual part. Monitoring the condition of the press, the used tool kinematics, and the current tool status is also referenced. All of this information is available in a detailed dashboard via browser and app for the machine operator and in an abstracted form for the production manager. If a defect occurs, the affected parts can be precisely identified. In addition, all data is available to identify and understand the cause of the error. This way, the OEE and resource efficiency are maximized in the Smart Stamping vision, see Figure 5.

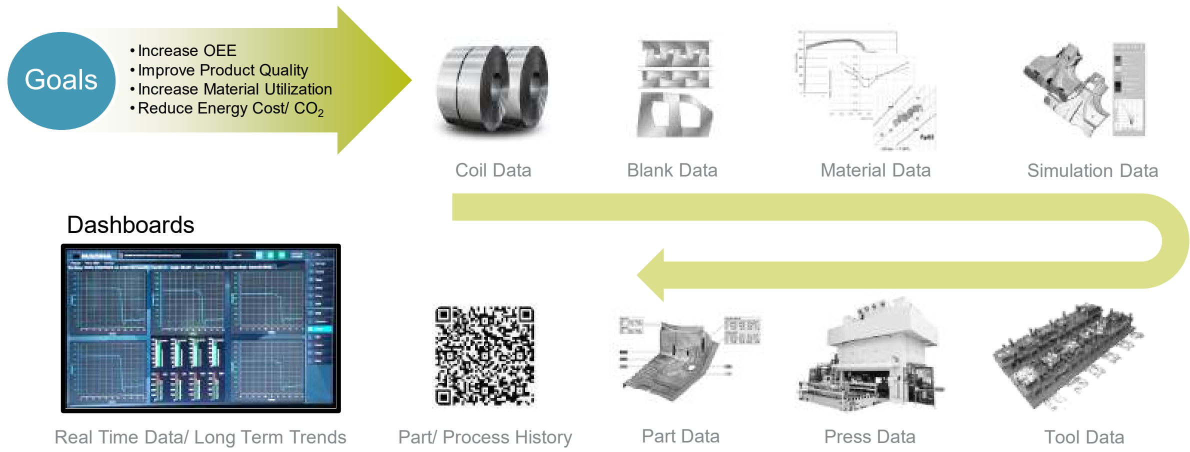

Figure 5: The Magna Cosma Smart Stamping press shop

4 Summary

Stochastic fluctuations in production conditions can be particularly disadvantageous to deep drawing processes if they are not designed to be resilient. Smart stamping approaches can achieve a higher process stability by increasing resilience. In this work, different approaches with different levels of automation are presented and evaluated. There are already systems that automatically detect and reject defective components, adapt the production process after each stroke for the next stroke, and control the process in real time during the stroke. In addition to that, the prediction of optimal press settings based on incoming material properties is particularly discussed in this work. If the component quality is measured after forming, for example, through material inflow, feedback loops can be implemented to update the digital twin.

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MACHINING

“Success in manufacturing and machining comes down to precision and accuracy, without them, nothing fits.”

— Henry Ford

Efficient Machining Solutions for Sustainable Aircraft Production

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Abstract

This article deals with sustainability in aviation industry. Sustainability aspects are explained concerning operation of aircrafts, future aircraft concepts and the manufacturing of machined integral parts. Here, adapted raw materials, machining strategies, NC-simulation and use of machine tool aggregates lead to improvements in the shop floor footprint and sustainability.

Keywords: sustainability, aircraft, machining, NC-simulation, raw material

1 Extended Abstract

Sustainability has become the most challenging strategic goal for the next decades to stop climate change. In aviation sustainability is now an important part of business strategies and operations - whether through products, industrial sites or people. Specific targets for the main fields of sustainability are clearly defined by timeline and key performance indicators like reduction of CO2-emission, energy, waste etc. for products and industrial footprint including the supply chain.

Civil air traffic produces roughly 2% of overall CO2-emission caused by humans [1]. New aircraft concepts, more efficient turbofans and developments based on hydrogen propulsion are massively forced. Airbus has the ambition to develop the world's first zero-emission commercial aircraft by 2035. Earlier CO2-emission reductions can be achieved by fostering a full value-chain in Europe to produce synthetic sustainable aviation fuel (SAF). The objective for commercial aircraft is to achieve certification of 100% SAF in flight by 2030 [1].

When looking closer to the production of aircrafts, of course, the structures, their materials and manufacturing methods become more important. Bionically inspired lightweight designs lead to optimized aircraft structures and parts, while Aluminum alloys compete with composite based materials for application. Composites might have advantages concerning weight but disadvantages concerning recyclability and cost. Sustainable low-cost lightweight structures might be realized by mainly using Aluminum material with best recyclability. Beside composite and Aluminum, Titanium, Inconel and steel parts will still be used for high temperature and/ or for high stress applications [2].

Due to very high part variety for aircraft integral parts with relatively small batch sizes, machining out of plate material is still widely in use with a high ratio of scrap, up to 98% [2]. Despite sorted recycling of chips and remaining material of clamping connections has been implemented for years, more near net shape raw material like die forgings, extrusions, castings and additive manufactured blanks will alternatively be fostered to minimize material and machining energy resources. Especially two additive manufacturing methods are under development: metal powder bed fusion and wire welding. Premium AEROTEC is already qualified for manufacturing parts made by Titanium powder bed fusion and delivers for example manifolds for the A320-

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family [3]. In addition, Premium AEROTEC produces serial flying parts made from plasma wire welded raw material (so called DED parts; DED := Direct Energy Deposition)

For the machining processes several new approaches and developments will lead to more sustainability. However, in the price driven global market for machined parts sustainability just starts to become a unique selling point. High performance machining technologies enables higher material removal rates with higher outputs per machine. According to the Kienzle equation, higher feed rates cause less energy consumption per removed material volume. E.g. for Aluminum machining, doubling the feed rate reduces energy consumption of a milling cutter by more than 15% per part [4].

It is well known, that most of the energy consumption of machine tools are caused by aggregates. Here, especially coolant supply systems are in focus for energy savings. Frequency-controlled coolant medium pumps improve efficiency [5]. Today, machining operation specific coolant pressures can be chosen in NC-programs. Current developments in technological NC-simulations of milling processes will enable a calculation of current loads of operations with minimized coolant flow rates that are actually needed. Of course, specific energy control systems will more and more adapt energy consumption to different modes.

Hard metal machining leads to high tool wear. For Titanium machining Premium AEROTEC investigated tool wear depending as a function on cutting conditions like cutting speed, feed per tooth and width of cut. The developed tool wear model implemented in the technological NC-simulation enables a prediction of tool wear and simulated tool life times for the different machining operations in serial production [6]. Another research project deals with an automatic tool wear measurement for solid carbide milling cutters to minimize the removed material when regrinding. The overall target for reduction of the resource solid carbide by these activities is -30%.

The technological NC-simulation is another enabler to improve sustainability in machining. For new parts, that have to be produced, already optimized NC-programs reduce the number of iterative evolutions to qualifiy NC-programs ready for serial production. By using technological NC-simulation, milling loads can be optimized, chattering can be detected and also tool deflection be can visualized [5]. More efficient milling processes with better part quality, less scrap and shorter machining times per part lead to more sustainability.

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Enhance Chatter Prediction for Increased Productivity

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Abstract

Milling process instability due to regenerative chatter vibrations is a complex phenomenon that has been causing serious damages and imposing productivity limits in the manufacturing industry. Developing a reliable solution that complies with the practical capacities of a shopfloor brings economic and environmental benefits. This paper introduces a physics-supported probabilistic machine learning approach, where chatter monitoring data from one or multiple machines are effectively exploited under a federated learning scheme, also enabling the attained knowledge to be transferred to other machines and processes. The resulting probabilistic prediction offers added reliability by revealing unresolved uncertainties due to limited observation through arbitrary cuts. The approach offers extended applicability for chatter prediction in non-rectangular workpiece-tool interactions, which often occur in industrial milling. The effectiveness is evaluated through experimental case studies and shows a promising solution to the decades-old industry's struggle with the chatter issue.

Keywords: Chatter, physics-informed learning, Bayesian learning, non-rectangular tool engagement

1 Introduction

Chatter vibrations severely limit the productivity of all kinds of chipping machines threatening with severe damage on tool, workpiece or even machine. Since the pioneering study on regenerative chatter by Tlusty [1] in 1963, a lot of effort has been spent to first understand the phenomenon and then find an industrially viable solution for safe avoidance though going to the possible limits or even shifting them. With the stability lobe diagram (SLD) stemming from the zero-order solution (ZOS) by Altintas and Budak [2] a powerful means to distinguish stable and unstable parameter regions. For its setup cutting force coefficients (CFCs) and the frequency response function (FRF) at the tool tip are required, but due to changeover of the machine tool, wear and aging these are prone to considerable uncertainties. The setup of a reliable SLD is for machine tool users infeasible. In recent times artificial intelligence is applied in combination with the physics of SLDs. Postel et al. [3] used the ZOS supported by inputs from multiple artificial neural networks. Each network represents a specific component of the milling system Wegener et al. [4] proposed a modular model of the milling system, augmented with neural networks to account for unmodeled dependencies. To enhance the reliability of the predictions a probabilistic approach proved to be beneficial, as demonstrated by Schmitz et al. [5]. Ostad Ali Akbari et al. [6] improved the underlying physics-based model, specifically the critical model of holder-tool assembly with a distributed joint interface. This enhancement enabled effective information flow between various substructures, enabling federated and transfer learning. Additionally, they demonstrated how model uncertainties could be leveraged to guide experimental data collection through active learning. An extension of the approach from [6] to non-rectangular workpiece-tool interactions is also presented in this paper.

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2 Physics-based modeling for chatter stability analysis

To establish a comprehensive modeling framework that accommodates the vast variety of milling system configurations, the system is decomposed into subsystems, each representing a crucial player in process stability as illustrated in **Figure** . The advantage of this approach lies in enabling the dedicated refinement of subsystems based on their participation in various machines and processes. Moreover, the refined model of each substructure from one learning iteration can be transferred to new milling operations using transfer learning. Further details are explained in [6].

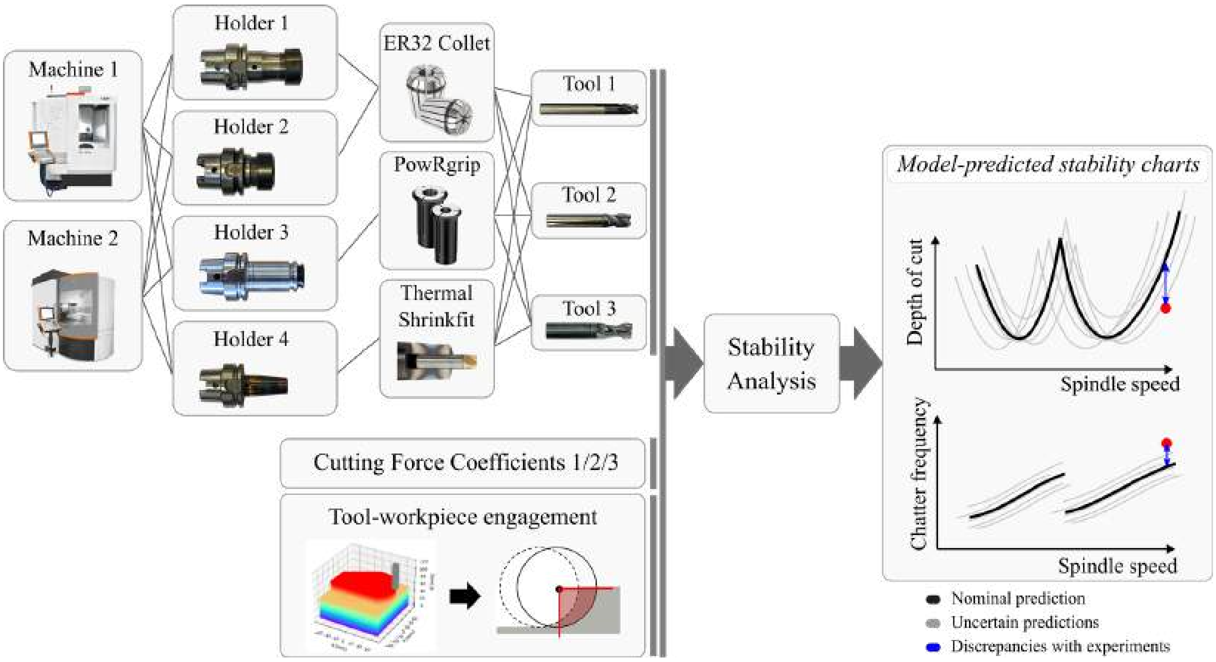

Figure 1: Modular representation of a milling system for stability analysis through physics-driven modeling.

This modular framework allows for a substructure coupling approach to combine the dynamics of different structural components, ultimately determining the FRFs at the tip of the end mill. Considering **Figure 2**, this is done using the following equation [6]:

$$\boldsymbol{\Phi}_{SHT,11} = \boldsymbol{\Phi}_{HT,11} - \boldsymbol{\Phi}_{HT,21}(\boldsymbol{\Phi}_{HT,22} + \boldsymbol{\Phi}_{S,33})^{-1}\boldsymbol{\Phi}_{HT,21} \tag{1}$$

Regarding the notation, the receptance matrix $\boldsymbol{\Phi}_{HT,21}$ is a 2-by-2 frequency-dependent complex-valued matrix that contains translational and rotational FRFs of the assembly HT when the excitation is applied at point 1 and the response is measured at point 2. This approach is known as Receptance Coupling Substructure Analysis (RCSA) and is explained in detail in [7].

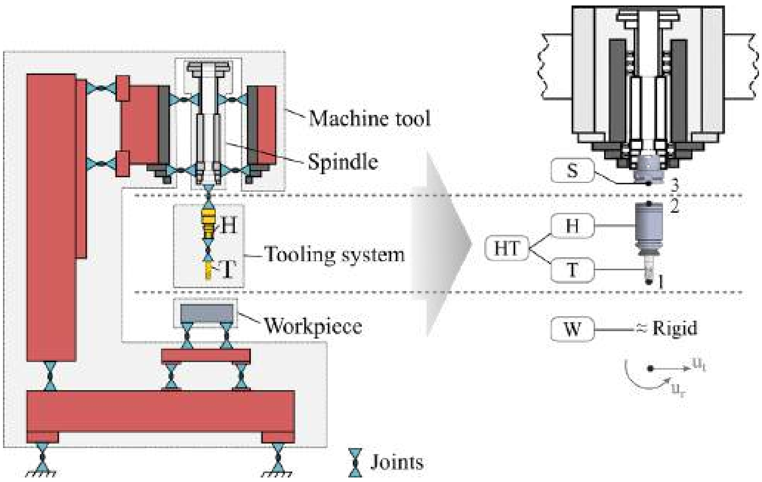

Figure 2: Substructuring approach for tooltip dynamics calculation.

The translational dynamics at the tooltip in X and Y directions $\boldsymbol{\Phi}_{SHT,11,tF}$ are then used in the ZOS to analyze chatter stability, which is based on delayed feedback characterized in the following equation:

$$det[\boldsymbol{I} - \frac{1}{2} K_{tc} \Delta a_p \sum_{i=0}^{N_e-1} \boldsymbol{A}_{0,i} (1 - e^{-sT}) \boldsymbol{\Phi}_{SHT,11,tF}] = 0 \quad (2)$$

With K_{tc} standing for tangential CFC and T for tooth passing period. The above expression includes a summation over directional coefficients to extend the applicability of the ZOS to general workpiece-tool interactions, where the engagement is discretized into N_e elements of rectangular engagement with the thickness Δa_p, as demonstrated in **Figure 3**. The directional coefficient for each element $\boldsymbol{A}_{0,i}$ is computed using its corresponding engagement angles of $\emptyset_{st,i}$ and $\emptyset_{ex,i}$, according to the formulation in [8]. Therefore, the cumulative load from all these elements is substituted into the transfer function of the closed-loop self-excited vibrations. This method is further explained by Budak et al. [9].

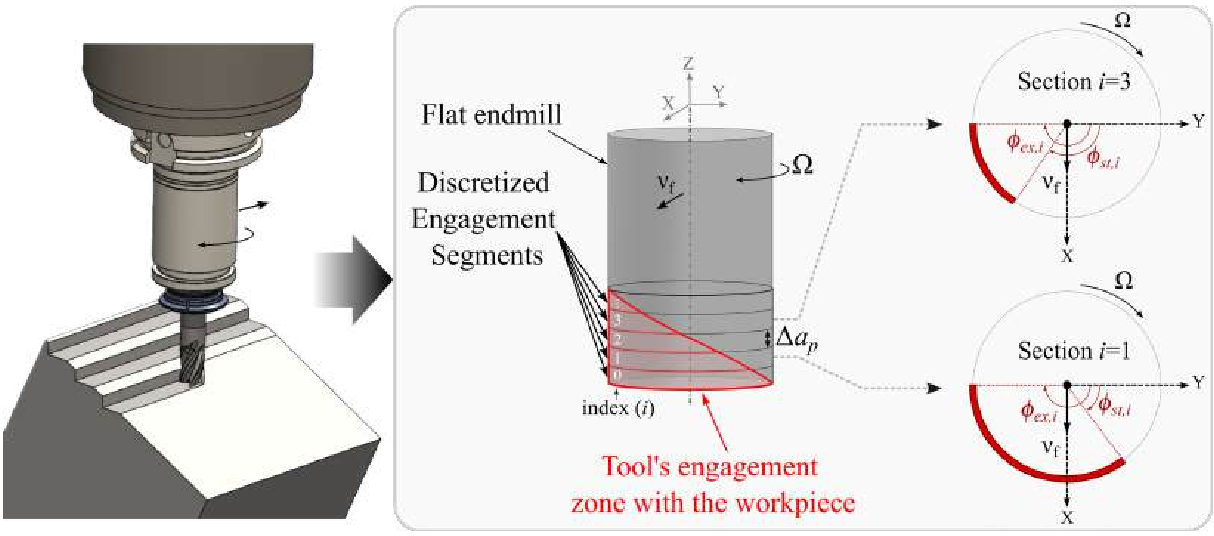

Figure 3: Discretized engagement for modeling a non-rectangular workpiece-tool engagement.

3 Bayesian learning and inference

Unlike the deterministic perspective which considers a definite value for a variable, the Bayesian perspective accounts for the entire spectrum of possible variable values along with their realization probabilities. Bayes' rule refines the probability distribution of model parameters according to their agreement with the training data through a likelihood function. The Bayesian learning framework in this study is based on [6], where the detailed model parameters and their distributions are outlined. To briefly recap the core equations, the Bayes rule

$$P(\theta|D) \propto P(D|\theta)P(\theta) \quad (3)$$

considers the following likelihood function to refine the prior $P(\theta)$ to the posterior $P(\theta|D)$, combining information from the stability state of stable cuts plus the information from the stability state and chatter frequency of unstable cuts:

$$P(D|\theta) = \prod_{i=0}^{N} [P(s_i = 0|a_{cr,model}) + P(s_i = 0|a_{cr,model})P(f_{c,i}|f_{c,model})] \quad (4)$$

where s_i stands for the experimental stability state of a cut with 0 being stable and 1 being unstable. The experimental chatter frequency is $f_{c,i}$. The likelihood from an unstable observation is established based on a sigmoid function using the difference between the model-predicted critical depth of cut $a_{cr,model}$ and the experimental axial depth of cut a_p with the hyperparameter k that adjusts the transition steepness:

$$P(s_i = 1|a_{cr,model}) = 1/(1 + exp\frac{a_{cr,model} - a_p}{k}) \quad (5)$$

and for a stable cut $P(s_i = 0|a_{cr,model}) = 1 - P(s_i = 1|a_{cr,model})$. In addition, for unstable cuts, the likelihood of a chatter frequency is computed according to a normal distribution centered around the mean value of the model-predicted chatter frequency $f_{c,model}$, with a hyperparameter standard deviation σ as:

$$P(f_{c,i}|f_{c,model}) = \frac{1}{\sigma\sqrt{2\pi}} exp[-\frac{(f_{c,i} - f_{c,model})^2}{2\sigma^2}] \quad (6)$$

In the end, the inference of the stability state at each process configuration can be computed through the following Monte Carlo estimations:

$$P(s^* = 1|D) = \frac{1}{N_s} \sum_{j=0}^{N_s} P(s^* = 1|\theta_j) \quad (7)$$

and analogously for chatter frequency:

$$P(f_c^*|D) = \frac{1}{N_s}\sum_{j=0}^{N_s} P(f_c^*|\theta_j) \tag{8}$$

These approximations are based on N_s samples of model parameters θ_j drawn with respect to their posterior distributions, for which an Evolutionary Markov Chain Monte Carlo (EMCMC) method is used in this study [10].

4 Applications and validations

The following steps provide a roadmap for deploying the proposed learning system to refine chatter prediction in an industrial environment. The following steps are required for establishing the learning framework:

1. Establish a database to store the geometrical dimensions of the holder and tool. This could be a simple tabular database or be connected to an existing database that some manufacturing companies already use. Alternatively, a camera can be placed inside the tool magazine to automatically detect the necessary dimensions through image processing. This information is used to create a model based on Timoshenko beam elements [11] and compute the dynamics of the holder-tool assembly.
2. Conduct impact tests once per machine tool by mounting a cylindrical dummy holder to the machine's spindle interface, as instructed in [12]. Characterize the machine tool dynamics by mathematically subtracting the effects of the dummy holder to obtain the machine tool FRFs at the spindle flange. Alternatively, approaches such as the machine tool dynamics identification using forced vibrations can be employed to obtain these FRFs [13].
3. Install a microphone on each machine tool for chatter detection through process noise analysis and record the chatter frequency at each instant.
4. Simulate workpiece-tool interaction based on the workpiece geometry and the NC program to calculate the interaction of the tool with the workpiece. Dedicated software packages are available for this purpose. Within the scope of this paper, the workpiece has negligible flexibility compared to the tooltip.

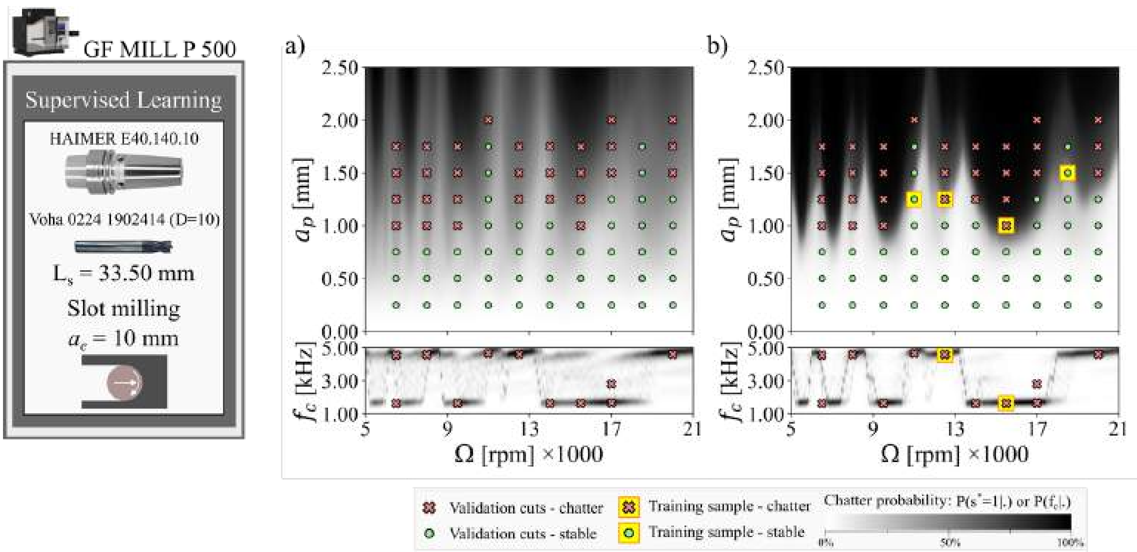

Figure 4: Probabilistic stability analysis for a single machine and process configuration. a) Prior stability inference and b) Posterior after training on indicated experimental data.

The validation of the proposed approach begins with the scenario illustrated in **Figure 4**, where a 3-axis milling machine with the detailed holder-tool combination performs validation cuts on an AL6082 workpiece block. **Figure 4**-a shows the prior probabilistic stability prediction without any experimental data training, revealing a high degree of uncertainty when relying solely on the physics-based model. In **Figure 4**-b, the highlighted points represent the training data used for Bayesian learning to refine model uncertainties. This demonstrates that incorporating even a small amount of training data can enhance the stability prediction accuracy, with the remaining uncertainty indicated by the gray regions.

The case study in **Figure 4** relied only on data collected from a single machine-holder-tool configuration and process. However, having a network of machine tools in a production line offers a valuable opportunity for multiple machines to learn from each other. In the case study in **Figure 5**, federated learning considers a machine tool with three different holder-tool combinations simultaneously in the learning process. Two of these combinations use a similar holder, thereby sharing their holder-tool joint parameters. Additionally, all three cases use similar tools and cut the same material, allowing them to link their CFCs. The refined model and posterior parameters can then be transferred to a new milling scenario, enabling it to have a more accurate prior prediction.

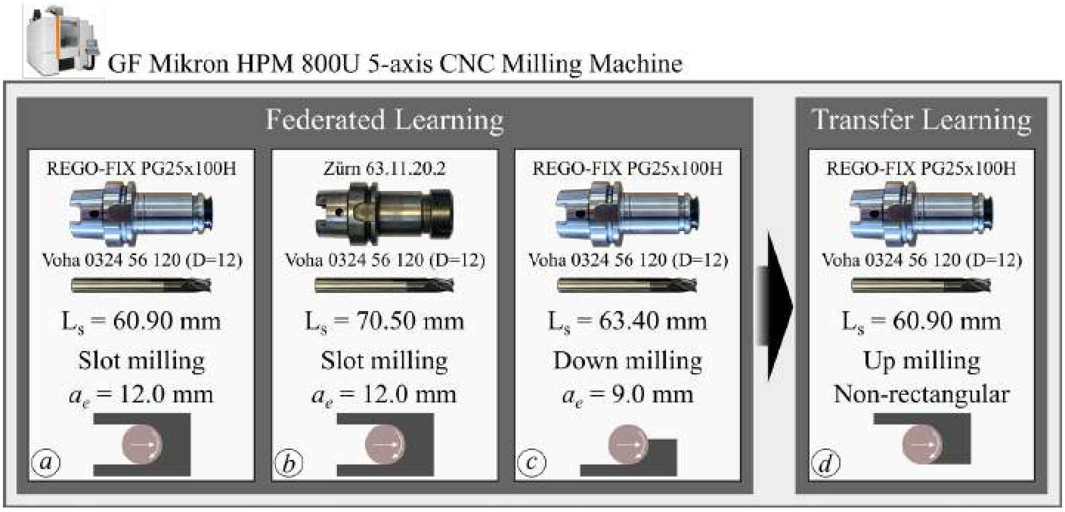

Figure 5: Federated learning by including three different structural arrangements. After training, model parameters are transferred to a different process for stability prediction.

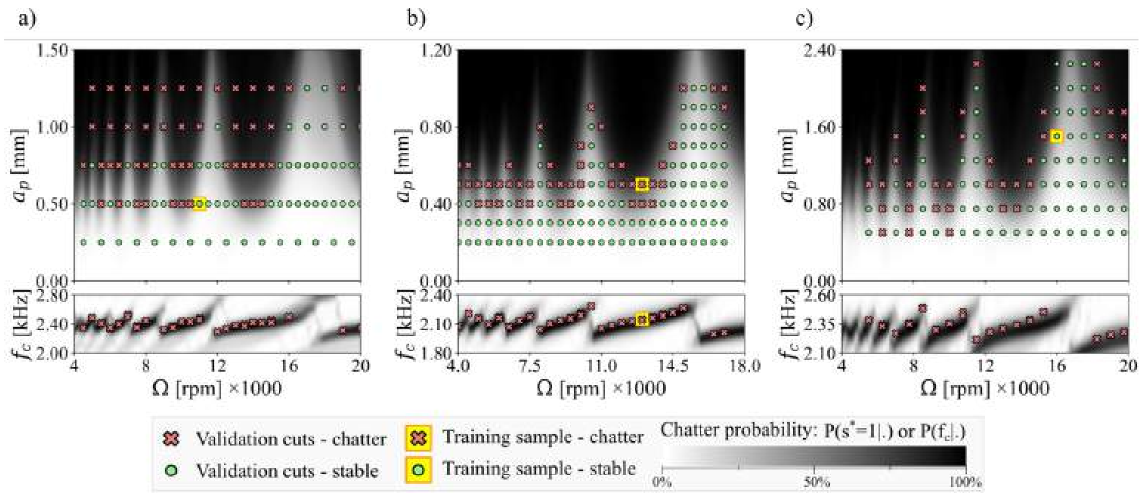

Figure 6: Posterior stability predictions from federated learning.

The resulting improvement from federated learning with limited training data is shown in Figure 6, illustrating the effectiveness of learning when multiple machines interact during training. The model is then transferred for stability prediction in a non-rectangular engagement. As seen in Figure 7, the proposed approach effectively predicts stability for non-uniform engagements.

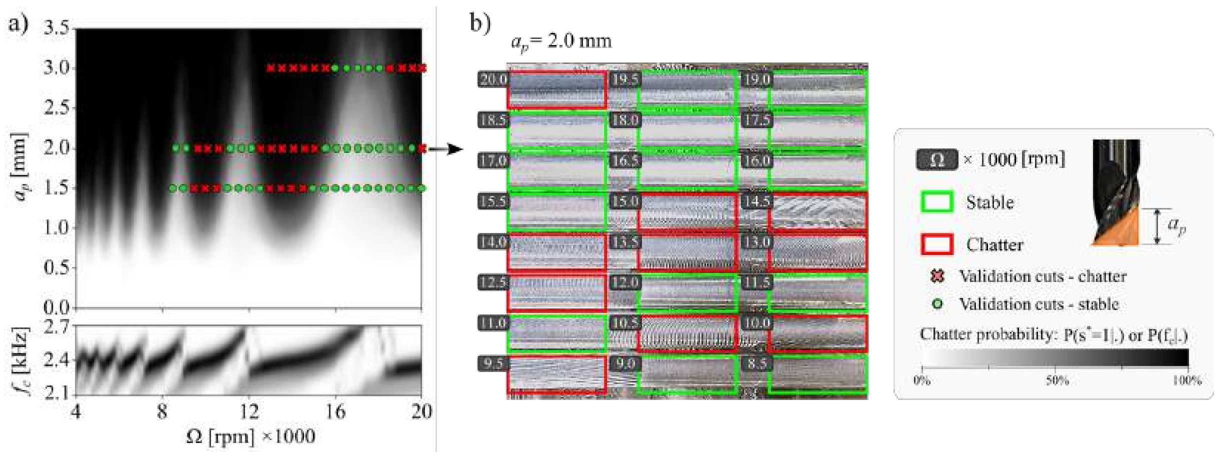

Figure 7: a) Transfer learning for stability prediction in non-rectangular workpiece-tool interaction, b) Surface quality and chatter marks on the workpiece surface after performing the validation cuts.

5 Conclusion

Despite extensive research on chatter suppression and various aspects in modeling, a robust, comprehensive, industry-friendly solution suitable for shop-floor implementation is still lacking. This paper adopts the promising strategy of physics-informed Bayesian learning and expands it to include general workpiece-tool interactions. The experimental studies have demonstrated the efficacy of the proposed method, while taking considerations for industrial implementation into account.

6 References

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Efficiency Improvements of Machining Processes based on Novel Simulation Developments and Detailed Process Chain Analyses

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Abstract

An increasing prioritization of efficient processes in machining production can be observed in order to focus on the aspect of sustainability in addition to economic machining. In the work presented here, optimization potential in in the design and manufacture of tools and tool holders was identified based on novel simulation developments and detailed process and process chain analyses. For the efficient use of cooling lubricants in ejector deep hole drilling, the tool design could be adapted with the help of Smoothed Particle Hydrodynamics (SPH) simulations. Another aspect is the development of advanced particle-damped tool holders, the use of which can significantly increase process stability during turning and milling. In a detailed process chain analysis, the manufacturing route of cemented carbide tools was investigated to identify energy consuming process steps and form a basis to optimize the resource-efficient reprocessing of the tools.

Keywords: ejector deep hole drilling, SPH simulation, particle-damped tool holders, tool reprocessing, energy efficiency

1 Introduction

Manufacturing accounts for about 23% of global energy consumption [1] and thus has a major influence on the emission of climate-damaging CO_2 emissions. Rising energy and raw material prices and a growing awareness of environmental consequences place high demands on manufacturing processes. When developing more efficient machining processes, the focus is therefore increasingly on energy consumption throughout the entire process chain in addition to increasing productivity. This is reflected in a large number of publications in the field of machining, in which a wide range of experimental and simulative approaches are used to realize energy-efficient machining processes [2].

Machining processes are a complex interaction of tool holder, tool, workpiece and cooling lubricant and must be examined in detail in order to identify optimization potential. In addition to experimental analyses, modern simulation systems are capable of realistically mapping complex interrelationships and offer detailed insights. The potentials that can be identified with a new simulation and detailed process and process chain analyses in this paper range from the improvement of tool design with regard to cooling lubricant supply and the optimization of dynamic tool behavior through the modification of tool holders to the analysis of energy-intensive process steps in tool grinding. By taking into account the manufacture and reconditioning of the tools, the entire life cycle of a tool is considered in addition to its performance in use when evaluating and optimizing the energy efficiency of machining processes.

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2 High productivity machining processes and resource-efficient use of cutting tools

When optimizing highly productive machining processes with regard to energy efficiency and the resource-saving use of tools, the energy consumption of the process itself must be considered on the one hand, while on the other hand there is potential in increasing the performance of the tools. With an average of 25.6 % of the total electrical energy used in machine tools, the cooling lubricant supply accounts for the largest share [3]. Modern and sophisticated methods of flow simulation allow complex processes such as ejector deep hole drilling to be analyzed with regard to optimizing the flow conditions. With the help of additive manufacturing, optimized tool geometries can be achieved that could not be produced conventionally.

When machining demanding materials, performance is often limited by the dynamic excitation of the tool, which has a negative impact in the form of chatter marks on the workpiece surface and increased tool wear. Here too, additive manufacturing provides the opportunity to increase the performance therefore the efficiency of cutting tools by allowing the integration of internal structures into tool holders that improve the dynamic tool behavior as particle dampers.

2.1 Efficient use of cooling lubricants based on Smoothed Particle Hydrodynamics Simulations on the example of ejector deep hole drilling processes

Deep hole drilling processes place high demands on the cooling lubricant supply and typically require high pressures and large volume flows and therefore a correspondingly high pump capacity. In addition to cooling and lubricating the highly stressed cutting edges, the coolant must also ensure the safe removal of chips from the bore hole [4]. The cooling lubricant supply in these processes accounts for a large proportion of the electrical energy required. Reducing the required pressures and volume flows by gaining a precise understanding of the flow behavior and optimizing the tool geometry therefore has a high potential for significant energy savings and the realization of efficient drilling processes. Ejector deep hole drilling is a special deep hole drilling method. The process does not require any special machine equipment and can be carried out directly on machining centers or lathes [5]. The tool consists of a drill head and a double tube system (see left side of **Fig. 1**). The cooling lubricant is fed to the drill head in the annular channel between the inner tube and the boringbar and is discharged together with the chips through the chip mouths into the inner tube. The process does not require a sealing between the tool and the workpiece, as a negative pressure is generated in the inner tube due to the Venturi-principle by special ejector nozzles (Section B in Fig. 1).

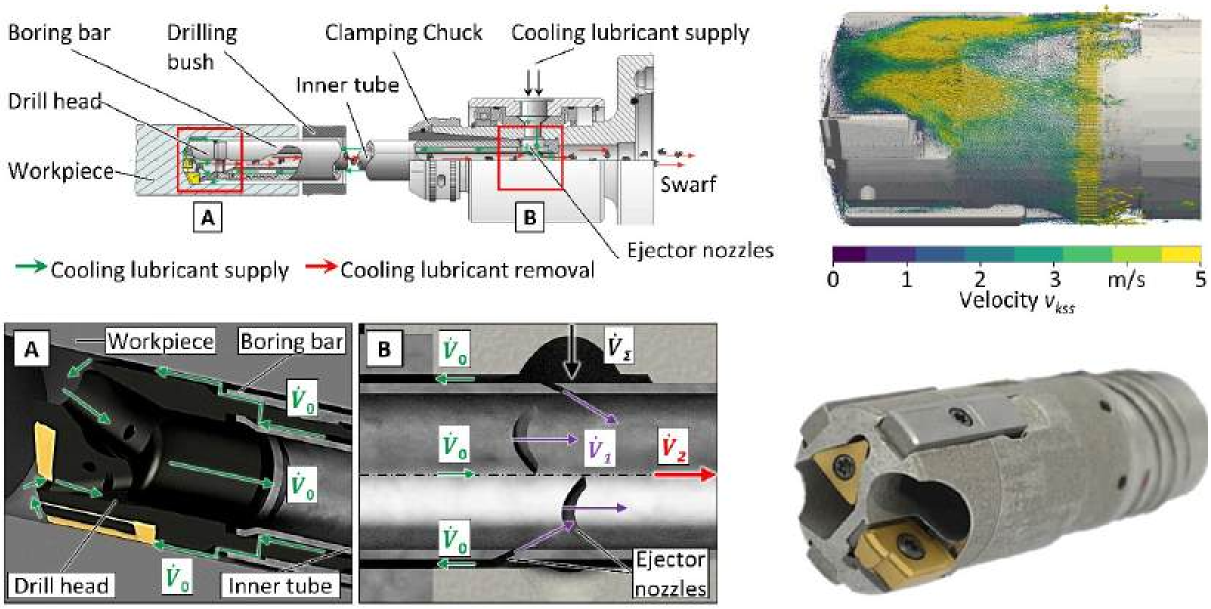

Figure 1: Functional principle of ejector deep hole drilling (left), SPH flow simulation and additively manufactured drill head (right)

The grid-free approach of Smoothed Particle Hydrodynamics (SPH) simulations is particularly suitable for the detailed analysis of the flow conditions during ejector deep hole drilling [6]. SPH is a meshless Lagrangian method in which the continuum medium is discretized by a collection of points, referred to as particles. In order to compute the physical attributes of fluid flow problems, SPH employs the solution of the Navier-Stokes (N-S) equations using the aforementioned points. This makes it possible to convert complex partial differential equations in time and space, such as the Lagrange form of the Navier-Stokes equations, into ordinary differential equations that can be solved with standard integration algorithms and enables a physically correct and reliable simulation of the cooling lubricant flow in systems with free surfaces and changing topologies. The mesh-free nature of SPH enables the modeling of changing surfaces and interfaces with relative ease. This quality renders SPH an advantageous method for problems such as the modeling of ejector deep hole drilling, where the fluid domain is in a state of constant evolution, which is a significant computational challenge when attempting to track it using conventional mesh-based methods. The simulation of the fluid flow for ejector deep hole drilling commences with an initially empty geometry of borehole and drill head. A constant cooling liquid inflow is positioned at the outlet bores between the boring bar and the drill head with a laminar flow and a flow velocity of 5 m/s. This value is based on experimental data obtained through high-speed recordings using particle image velocity measurements (PIV). The inflow continuously introduces fluid particles into the simulation, while the outflow, situated within the inner tube, removes these particles from the simulation domain. Consequently, the requisite computational effort is diminished in comparison to a constant particle setup. Around 275,000 particles are used in the simulation domain for one simulation run. This is maintained until a nearly steady state of the flow is reached. The simulations require approximately 10 days on AMD5950X machines with 14 cores. The measurement of the flow in experimental investigations provides input data for the simulation on the one hand, but also serves to validate the simulation results on the other. Visual access to the coolant flow for the optical evaluation of the flow field with a high-speed camera system is made possible by a transparent ejector drilling system made of polycarbonate and the use of polyamide tracer particles in the coolant.

Taking into account the mechanical tool load caused by the feed force and drilling torque, drill heads with different modifications were designed. Based on the flow simulations, three tool areas were selected for the implementation of the optimization measures. These were evaluated with the help of the SPH simulation and compared with regard to their cooling lubricant flow behavior. Firstly, the chip mouth opening on the drill head was widened in the area of the outer cutting edge to optimize chip removal and prevent chip clogging. Furthermore, the inner contour of the drill head was adapted to a rotor shape. This ensures that the tool rotation transfers the rotational energy to the swarf and accelerates the fluid. Furthermore, the cooling lubricant outlet holes on the drill head were varied in their shape and inclination. This results in a targeted supply of coolant in the direction of the chip formation zone with increased flow velocity, which can reduce tool wear and temperatures in the process. The flow-optimized drill head shape selected on the basis of the simulation was additively manufactured from the tool steel X3NiCoMoTi18-9-5 (1.2709) using the laser powder bed fusion (LPBF) process. Post-machining was only required in the close-tolerance areas of the indexable insert seats, the guide pad seats and the connecting thread.

The performance of the flow-optimized additive manufactured drill heads was analyzed in experimental tests. It was found that the optimized geometry in the area of the coolant outlets and the modified chip mouth have a positive effect on the cooling lubricant flow and the removal of chips. The ejector effect, which is essential for ejector drilling and is responsible for the negative pressure in the inner tube, occurred at a significantly lower volume flow. The experiments demonstrate that a complete avoidance of chip clogging and the resulting drill head wear is achieved, resulting in a longer tool life of the outer cutting edge. Thanks to the simulation-based design of the drill head, an energy-efficient, resource-saving and process-reliable deep hole drilling process could be realized. For cutting speeds of v_c = 80 m/min and a feed rate of f = 0.2 mm, the required coolant volume flow rate could be reduced by up to 42.72 % ($\dot{V}_\Sigma$ = 29.5 l/min) compared to the standard tool ($\dot{V}_\Sigma$ = 51.5 l/min).

2.2 Development of advanced particle-damped tool holders to increase process stability in wide parameter ranges

When implementing efficient cutting processes, negative effects such as the occurrence of unwanted process vibrations, which are associated with higher cutting parameters, often prevent an increase in productivity. This occurs in particular when the stability of the machine tool is low, with long overhanging tools and when machining demanding materials that tend to form segmented chips. The process vibrations have a negative effect on tool wear and the resulting machining quality. Additive manufacturing enables the realization of complex particle-filled structures inside tool holders. The effect of these particle dampers is based on impact and friction processes between the individual particles in the cavity, which dissipate vibration energy from the system and dampen the machining process.

As part of the investigations, indexable insert holders and HSK63 tool holders were manufactured from tool steel X3NiCoMoTi18-9-5 (1.2709) using the LPBF process. The shape of the cavities and the inner structure made of modified truncated octahedron elements is based on preliminary investigations and was constructed using parameterized algorithms [7]. **Figure 2** shows the design of an additively manufactured indexable insert holder on the left with a cross-section of the cavity including the inner structure. The HSK63 tool holder shown on the right has a hybrid structure and is created using a conventionally manufactured HSK63 blank as the basis for the additively manufactured part containing the particle damper.

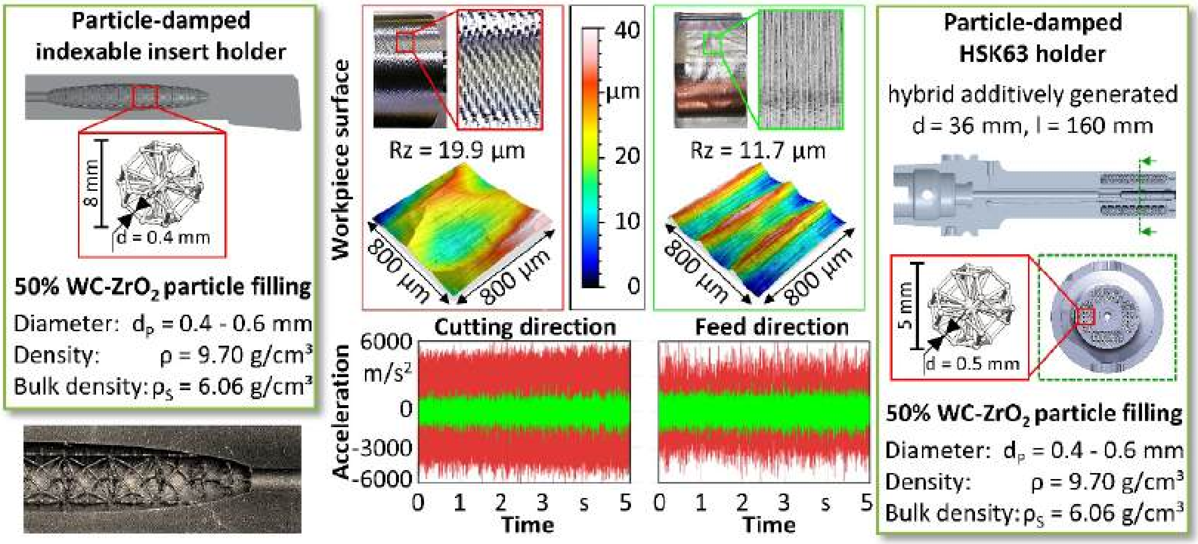

Figure 2: Additively manufactured tool holders for turning (left) and milling (right) with integrated particle dampers, surface quality and acceleration measurements for turning HSX®130 (middle)

In addition to the shape and surface structure of the cavity, the detailed investigations of the integrated particle dampers also focused on the powder material and the filling level of the cavity. In turning tests, a 50% filling of the cavity with WC-ZrO_2 particles was identified as particularly suitable. The middle of Figure 2 shows the measurement results for turning experiments of the bainitic steel HSX®130. The results of the conventional holder in red show a comparatively poor surface characterized by process vibrations and chatter marks, while the surface when using the particle-damped holder (green) is characterized only by feed marks. The acceleration measurements in the cutting and feed direction also demonstrate the excellent effect of the particle damper.

In relation to investigations with the additively manufactured HSK63 tool holder during milling, a 50% WC-ZrO_2 filling also has the greatest damping effect [8]. The harmonic response functions were determined with the aid of targeted excitation of the tool system using an impulse hammer. A simulative estimation of the stability limits was used to identify interesting speed ranges for the detailed experimental analyses. In comparison between a conventional tool holder and the additive manufactured holder with particle damping, the cutting depth up to the occurrence of chatter vibrations and thus the minimum reference stability limit could be increased by at least 146%. The use of tool holders with particle damping thus leads to a significant damping of process vibrations in both turning and milling operations. This enables more efficient and productive machining processes by realizing better component qualities and increasing productivity through the use of higher cutting parameters. Reduced tool wear enables the resource-efficient use of tools and leads to energy savings, as the manufacture and reconditioning of tools must be taken into account when assessing machining processes.

3 Potential to improve the resource-efficient use of cutting tools due to the analysis and understanding of the interactions in their reprocessing

In addition to improving tools and the machining processes themselves, companies are increasingly focusing on the manufacture and reconditioning of machining tools when considering their overall energy and resource efficiency. A key part of the endeavor to reduce CO_2 emissions and uncover optimization potential is the accurate quantification of a company's carbon footprint.

The Greenhouse Gas Protocol provides an internationally recognized framework for quantifying and reporting greenhouse gas emissions. It divides emissions into three areas: Scope 1 comprises direct emissions from own or controlled sources, Scope 2 refers to indirect emissions from the consumption of purchased energy, and Scope 3 includes all other indirect emissions along the value chain. In order to be able to calculate Scope 3 for parts production as well, the footprint of the cutting tools must be known. The production route of cemented carbide tools was therefore analyzed using the example of a 6.8 mm solid cemented carbide drill. The manufacturing route of a cemented carbide twist drill initially comprises the production of blanks, whereby powder production, moulding and sintering are important in addition to the extraction of raw materials. This is followed by the process steps of grinding the sintered blank. The ground tool body is usually subjected to cutting edge preparation and finally coated. A worn tool can be reconditioned after use by regrinding the tool and subjecting it to cutting edge preparation and coating again. To quantify this, the individual tool manufacturing processes were analyzed step by step. At the same time, a three-phase power measurement of the system and all peripheral devices, such as cooling lubricant pumps, was carried out on the machine tools. This made it possible to determine the electrical energy required to manufacture a single drill. **Figure 3** shows the relative results of these measurements.

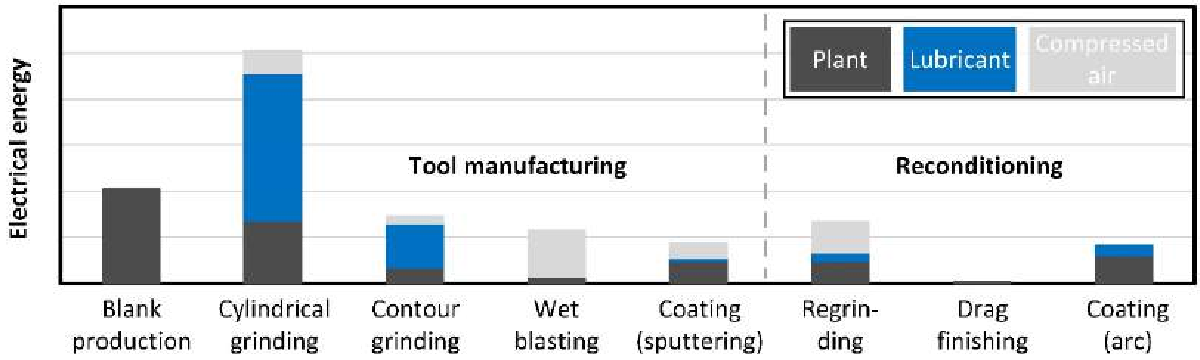

Figure 3: Energy consumption in the production of a solid carbide twist drill with d = 6.8 mm.

The investigations into the manufacture of cemented carbide tools have yielded key findings. In particular, the high proportion of secondary processes, such as the provision of compressed air and cooling lubricant, was identified as a significant energy consumer. This indicates a large optimization potential that can be realized through a targeted and adapted supply of these media. In addition, the investigations show that reconditioning worn tools can lead to considerable savings in electrical energy and the associated emissions. This enables companies to significantly reduce their CO_2 footprint in production without significantly affecting tool life. A circular economy should be the overall aim, whereby tools that can no longer be reground should be fed into the recycling process separately according to their carbide composition.

The high proportion of cylindrical grinding processes should be noted, which is explained by the time-intensive nature of these processes on tool grinding machines. More resource-efficient production could be achieved through the use of cylindrical grinding machines. In future, the centerless grinding of the sintered blank and secondary processes such as washing and cutting should also be included in the analyses in order to identify further potential for optimization.

As Figure 3 shows, a high amount of energy is necessary for the production of the blanks of cemented carbide cutting tools. The reprocessing of worn tools offers the opportunity to extend their life cycle. Therefore, it contributes to the enhancement of the sustainability of the use of the tools as well as to the saving and efficient use of resources. In this context, the process route for the reprocessing of cemented carbide cutting tools has to ensure highly-productive cutting tools. Moreover, the process chain of the reprocessing has to fulfill economic achievements as well. In order to contribute to both, research concerning the reprocessing of cemented carbide drilling tools is focused in a collaborative project together with the GFE - Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V. and partners from industry. The reprocessing of drilling tools comprises several process steps, which are shown in **Figure 4**.

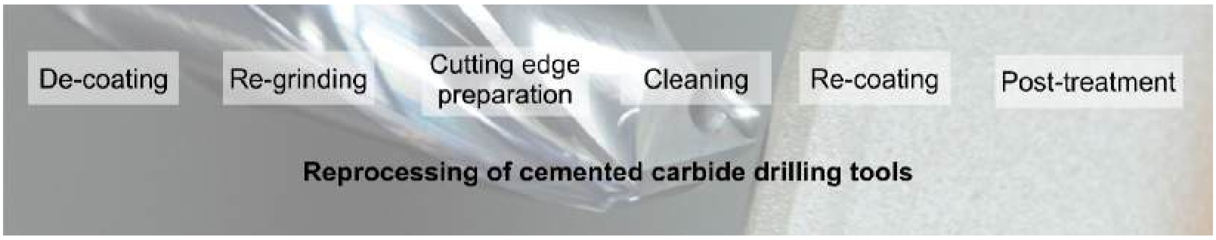

Figure 4: Process steps in the reprocessing of cemented carbide cutting tools

Initially, the process configurations and the influences of the individual process steps of de-coating, re-grinding or the post-treatment on the substrate and the tool performance are examined. Based on that, different process routes along the process chain in reprocessing shall be conducted and their influence on the performance and on economic aspects should be considered. The main focus will be on the interactions between the process steps as they are a key factor to build a fundamental understanding for the reliable reprocessing of cemented carbide cutting tools.

4 Conclusion and Outlook

High demands on productivity with a simultaneous focus on resource-efficient production with the lowest possible waste, low energy consumption and a small carbon footprint require continuous developments of tools and processes and the detailed analysis of process chains. This is the only way to identify and exploit available savings potential. As part of the investigations described, great progress was made through the use of innovative and complex simulation systems, targeted tool optimization with the help of additive manufacturing and detailed analysis of the energy consumption of numerous process steps in the life cycle of a cutting tool. In addition to reducing the energy required for the cooling lubricant supply and increasing productivity in turning and milling by means of particle-damped tool holders, a better understanding of the energy consumption in the production of cutting tools in particular provides approaches for making machining processes more efficient in the future.

5 Acknowledgements

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Adapt, Innovate, Transform the Future of the Machining Industry in a Volatile World

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1 Extended Abstract

Discourse on challenges in the Automotive Manufacturing Evolution, MAPAL's Role, and the Integration of X-Forge PRODaaS and AI-Driven Automation.

The automotive manufacturing sector is undergoing a profound evolution, driven by advancements in both the machining and automotive industries. The following scientific developments have been instrumental in this transformation:

1. Industry 4.0 (I 4.0) and Cyber-Physical Systems (CPS): The integration of cyber-physical systems within manufacturing has led to the emergence of smart factories, characterized by their autonomous decision-making capabilities, facilitated by IoT and data analytics.
2. Additive Manufacturing: Additive manufacturing, or 3D printing, has revolutionized component fabrication, enabling the production of complex geometries and contributing to vehicular lightweighting.
3. Electrification and Autonomous Technologies: The shift towards electrification and autonomous vehicles has necessitated novel manufacturing methodologies, including the development of specialized components like high-density energy storage systems.
4. Sustainable Manufacturing: The industry's focus on sustainability has led to the adoption of eco-friendly processes, the use of recycled materials, and the exploration of renewable energy sources.
5. Artificial Intelligence and Machine Learning: AI and machine learning algorithms have been applied to optimize manufacturing operations and enhance process efficiencies.
6. Material Science Innovations: Advances in material science, such as high-temperature alloys and smart materials, have improved vehicular performance and safety.

MAPAL has responded to these scientific advancements with precision tooling innovations, engineering acumen, tool management ecosystems, and automated process optimization. These contributions align with Industry 4.0 principles and address the automotive industry's challenges.

Significant investments in knowledge automation through selection and configuration engines has undertaken by MAPAL in recent years. These AI-based solutions are designed for intelligent machining processes either deployed directly to customers being part of a Smart Factory or used to deliver towards market demands in terms of MAPALs own process performance in engineering and process layouts. The applications include quality inspection of tools, cause analysis in production processes, goods logistics, and knowledge preservation or transfer. This focus on AI and digitalization ensures significant gains in sustainability, efficiency, and knowledge preservation.

The X-Forge PRODaaS (Productivity as a Service) research project represents these initiatives in a collaborative effort to develop a success-oriented business model for metal processing. This project aims to enhance productivity, process stability, and cost-efficiency through a package that includes machine tools, cutting tools, and IT services. The project leverages self-learning AI algorithms to intelligently recognize various machining

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situations and autonomously optimize process parameters, thereby improving machining quality and reducing component wear.

By integrating the X-Forge ProdAAS project and leveraging AI-driven automation, MAPAL is poised to deliver comprehensive solutions that address the current and future needs of the automotive industry. These efforts underscore MAPAL's commitment to leading the industry towards a sustainable and technologically advanced future.

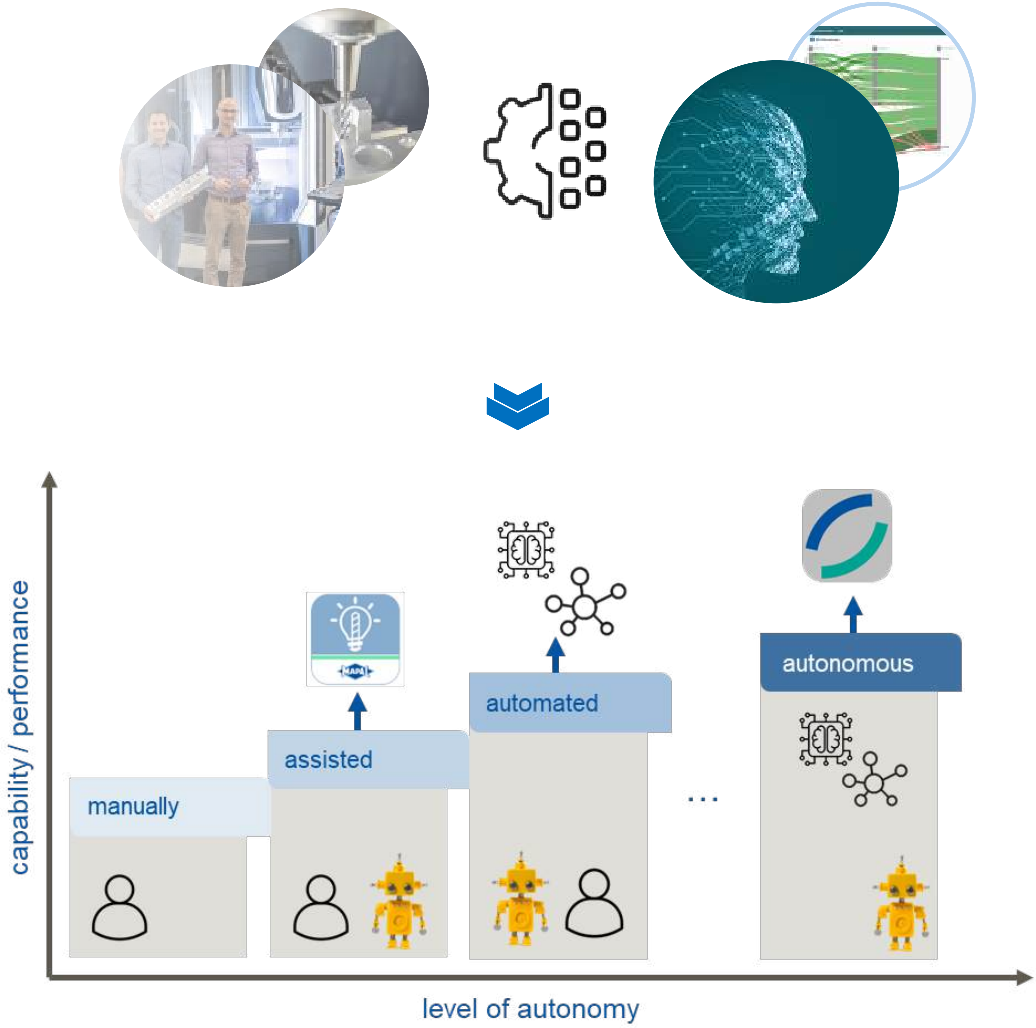

Figure 1: Transformation of knowledge application to drive manufacturing performance

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Simulation-based Control of Tool Wear and Lifetime for Titanium Machining

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Abstract

The prediction of tool life time in machining processes has been subject to research since the beginning of machining technology itself. Already in the early 1900s Taylor [1] found a basic correlation between tool life time and cutting velocity in turning. The Taylor equation has later been improved by also taking the chip thickness into account. However, not the equation is the problem in computing the tool life time but the parametrization for a certain pair of tool and work material. Especially for the machining of titanium alloys with sharp tools where the tool wear mainly consists of smaller or greater splintering of the cutting edges it is hard to determine the state of a somehow worn cutting edge as a scalar value. This makes it hard to measure the progression of the tool wear from a new tool towards a finally worn one. Especially the point in time at which the final wear, i. e. the end of the tool life, is reached is hard to determine. Another problem that is related to tool wear is the effect on the cutting forces. As far as it is not possible to simulate the tool wear progression it does not make sense to try to predict the point in time where the end of tool life is reached.
Measurements of the spindle torque with differently worn tools have shown that a simple extension of the Kienzle equation enables the inclusion of the tool wear into the cutting force computation. Vice versa, when the undeformed chip form is known it is possible to recompute the current wear state from the spindle torque. This enables the measurement of both the tool wear progression and the end of tool life and therefore to develop a tool wear model that is taking the undeformed chip form into account. This allows the computation of the tool wear progression even along any NC-program with continuously changing undeformed chip forms.

Keywords: titanium, tool life, tool wear model, milling simulation, cutting force model

1 Introduction

The modelling of tool wear along an NC-program can save production costs by reducing the probability of tool breakage and by enabling the usage of tools for as long as possible. So far, an automatic tool change is executed when the tool has expended its specific constant life time in G1-mode regardless of what kind of operation the tool has performed during that time period. Therefore, tools may be worn out before the tool change if they have encountered adverse conditions or they may still be in good shape otherwise.

By simulating tool wear, it is possible to compute the feed rate in a way that ensures the desired life time on the one hand, and on the other hand, to shift the point in time when the automatic tool change will occur. For this, a wear model has been developed that is based on a scalar value (i. e. the wear state r_c) that can be measured by the spindle torque or the cutting force, respectively.

Recently, the modelling of tool wear has been mainly related to FEM-simulations [2,3] which are applicable for technological investigations but not for the industrial usage in serial production. Other approaches like [4] apply wear models on a machining simulation which use discrete workpiece models like dexel boards to obtain the uncut chip shape, which is then correlated to the tool life-time. Thereby, the tool life-time is measured

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conventionally. Dexel models need a high resolution in order to render even small undeformed chips. Therefore, this approach is not applicable to aircraft frames of sizes up to a length of six meters.

2 Constant Offset in Spindle Torque and Kienzle Equation

It has been found that especially sharp tungsten carbide tools – as used at Premium AEROTEC – in first approximation apply a constant offset to the spindle torque rather than a factor when they are worn. This implies that there must also be a constant offset to the cutting force model (e. g. the Kienzle equation). This offset – called r_c – has the unit N/mm like a specific cutting force. Therefore, it is an additional force per mm of the cutting edge that is additionally produced by the current tool wear. When performing cutting tests with constant cutting parameters (axial immersion a_p, radial immersion a_e, cutting velocity v_c, and feed per tooth f_z) and measuring the spindle torque (e. g. by reading the related variable from the NC-controller or using a process monitoring system) the value r_c can be recomputed using a milling simulation by adjusting r_c in a way that the simulated spindle torque equals the measured one. By comparing r_c to the visual appearance of the cutting edge the additional specific cutting force at the end of tool life was determined as 40 N/mm. This is the point where the cutting edges appear strongly damaged but can still be reground.

With this, we have a scalar value r_c that describes the wear state of the cutting edge for the first time. Herewith, it is possible to perform cutting tests in order to parametrize and enhance a wear model like the enhanced Taylor equation [1].

3 Wear Model

The wear model, at first specific for a tungsten carbide tool of diameter 25 mm (Figure 1), mainly consists of the enhanced Taylor equation with an additional extension to account for the entry chip thickness [4]. First, we compute a value e_s called *life time equivalent* e_s:

$$e_s(a_e, v_c, f_z) = a_e^a \cdot v_c^b \cdot f_z^c - d \cdot h_e.$$

Hereby, h_e is the entry chip thickness which is the uncut chip thickness at the point in time where the cutting edge enters the material at the beginning of each cut. The parameters a, b, c, and d were calibrated by milling tests so that e_s was approximately equal for different parameters when the related tool life time was equal. It turned out that the tool life time itself is not generally linear in e_s.

Figure 1 shows the results of milling tests with varying milling parameters. With a = 0.674, b = 1.497, c = 0.016, and d = 0.016 the results best fit to a square function. This square function applied to the tool life equivalent e_s is the final model to determine the tool life time.

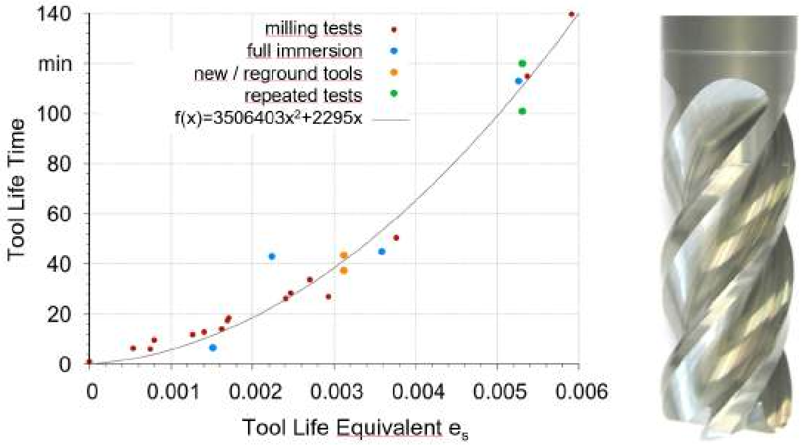

Figure 1: Results of tool life measurements (left) for the tungsten carbide tool with diameter 25 mm (right).

4 Control of Tool Wear and Life

With the tool life-time model the milling simulation can now compute the milling parameters along the NC-program in constant time steps (by a non-discrete approach for modelling the uncut chip form [6]) and compute whether the wear rate is within the desired window, too low or too high. In case of excessive tool wear, the feed rate can be reduced in order to achieve the desired life-time. In case of too low wear the feed rate can be increased if it is not limited by any other parameter like maximal force or chip thickness. Another possibility is to manipulate the elapsed time in G1 mode that is stored in an NC-controller-variable in order to achieve a longer usage of the tool. In this way the tool wear can be controlled in order to maximize productivity.

5 Conclusion

With the wear state r_c defined as an *additional* specific cutting force it is possible to describe the current tool wear state as a scalar value instead of the commonly used measurement of the width and depth of wear marks. By measuring the spindle torque while conducting wear experiments one can recompute the current wear state r_c, which leads to detailed data of the wear progression. It is no more necessary to perform microscopic measurements after each machined line of the tool path. This detailed data was the base for the development of a tool wear model which can also be applied on arbitrary NC-programs in order to optimize the usage of tungsten carbide tools.

Since the tool wear is modelled as an additional specific cutting force, it can be directly fed back into the cutting force model in order to compute the increase of the cutting forces along the tool path. This also enables the prediction of the point where the tool may be overloaded absolutely.

Future work will focus on the application of the same method on inserted tools on the one hand and on the machining of steel on the other hand.

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Improving machining efficiency by machine system intelligence

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Abstract

Digitalization and the implementation and application of sensor integrated 'intelligent' tools, fixtures and machine tool components provide a huge potential regarding the optimization of manufacturing systems in terms of productivity, quality, flexibility, reliability and availability as well as economic viability. Moreover, these approaches can essentially contribute to a reduction of energy and resource consumption and, thus, to an improved efficiency with respect to the environmental impact of production. This publication presents some exemplary technologies and discusses their potential regarding a reduction of the CO2 footprint in manufacturing.

Keywords: Digitalization, sensor integration, efficiency, carbon footprint

1 Introduction

With the aim to overcome current challenges such as raising production cost in high-wage countries and increasing skilled labor shortage, and in order to improve manufacturing flexibility, availability and efficiency, more and more industrial developments as well as scientific research are focused on automation solutions, digitization, specific implementation of machine learning and the integration of 'system intelligence' up to autonomous functionality and self-optimizing machining systems [1]. Modern communication technology, control interfaces and sensor integrated devices such as tools and machine components enable interconnected manufacturing environments with distributed multi-physical data acquisition, information processing and adaptive optimization control loops [2,3]. In order to elaborate suitable solutions of digitalized production systems and factories, sophisticated laboratories, development and test facilities were established recently, as for example the 'DigiLab' at the Institute for Machine Tools (IfW) at the University of Stuttgart (Fig. 1). In view of the climate change and considering the reduction of energy and resource consumption in production as a requirement of outmost importance, the target of optimization must include not only productivity, quality and economic viability but also transparency regarding the environmental impact and the minimization of the carbon footprint of manufacturing. Against this background, this paper provides an overview of exemplary 'intelligent systems' for machining and highlights the related environmental effects by an analysis of CO_2-equivalents. As can be seen by the presented solutions and findings, innovations in the field of manufacturing equipment and machine tools can contribute to a higher efficiency of production also with respect to environmental aspects.

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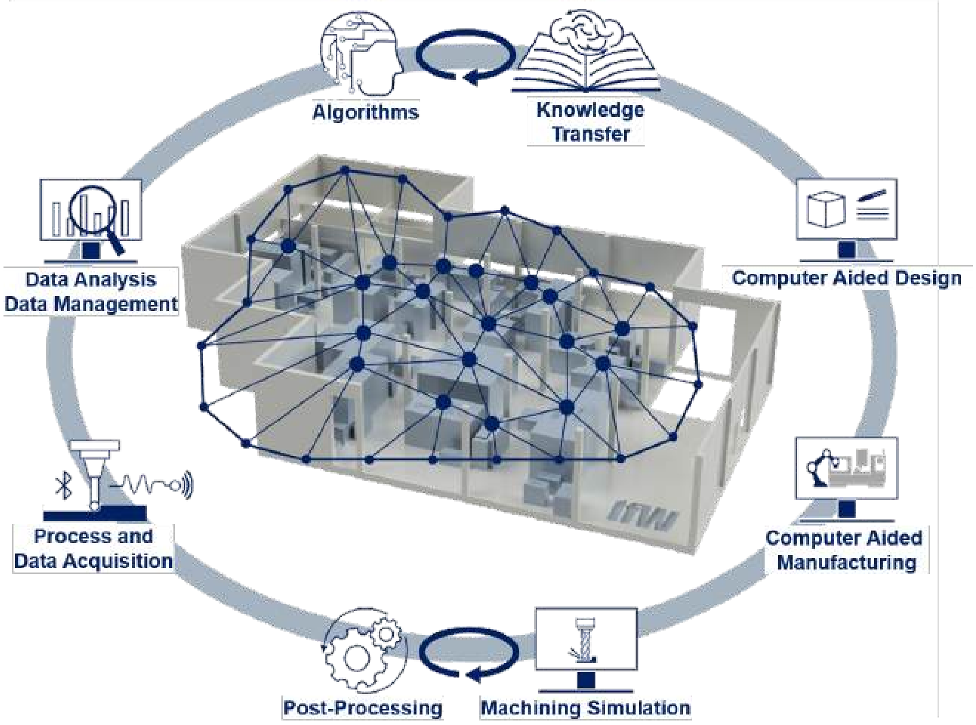

Figure 1: IfW – "DigiLab" for digital solutions in manufacturing (research, development and education).

2 Sensitive clamping of thin-walled workpieces

Lightweight design and the reduction of material usage in components and products by means of structural optimization lead to thin-walled workpieces that have to be machined with appropriate manufacturing machines and equipment. Thin-walled workpieces tend to vibrations in machining operations and they are prone to distortions due to residual stresses which are released and induced by the material removal [4]. Moreover, sensitive workpiece clamping is necessary in order to on the one hand avoid mechanical loads that deform the part but, on the other hand, to ensure stable and robust fixation even bearing process forces and gravitational or inertial influences. For this purpose, a sensory chuck jaw was developed at the IfW (Fig. 2) [5].

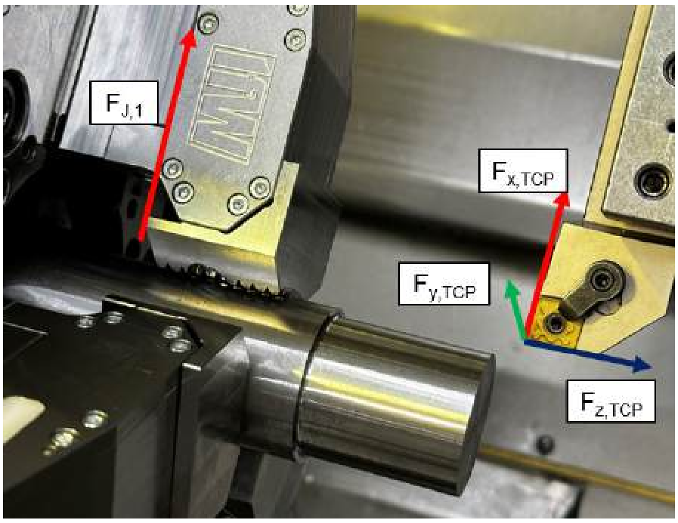

Figure 2: Sensory chuck jaw for turning applications.

This sensory clamping element allows for a direct measurement of clamping forces that act on the workpiece during the machining processes. In the case of thin-walled parts, these clamping forces can provoke workpiece deformations and, thus, affect the final accuracy of the part. As the stiffness of the workpiece decreases with progressing material removal, deformations and deviations from the desired shape increase and the stability of the clamping can fall below a critical state. The sensory jaw enables a sensitive monitoring and adjustment of clamping forces, and, by this, contributes to an improved capability and performance in machining thin-walled lightweight parts.

3 Semi-active lightweight high-performance tool

In order to significantly reduce the mass of an exemplary industrial high-performance milling tool but to improve its machining performance at the same time, an innovative semi-actively damped tool structure incorporating a hybrid material combination was realized at the IfW (Fig. 3) [6]. The tool with a diameter of 100 mm, a length of 320 mm and 44 cutting inserts consists of a topology optimized hollow steel body with particle dampers, an internal CFRP tube and an adjustable magneto-rheologic fluid (MRF) damper. Compared with the industrial tool, a mass reduction by 36% is achieved. Due to the improved dynamic properties, the material removal rate in milling steel 1.057 (AISI 1024) can be increased by a factor of eight and the surface roughness of the machined part can be reduced drastically at the same time. In order to allow an adjustment of the MRF damper to the actual process conditions and tool temperature states, a multi-sensor system and data processing and communication electronics are integrated into the tool. The multi-sensor system comprises temperature, acceleration, force and acoustic emission (AE) measuring functionality.

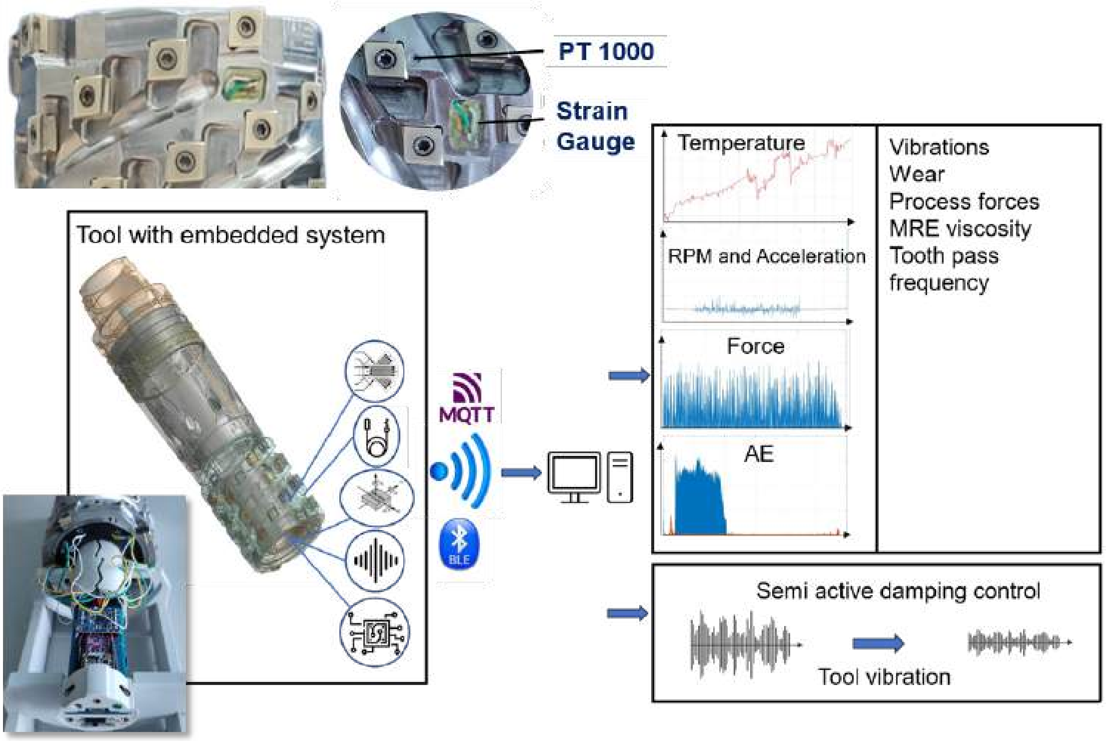

Figure 3: Lightweight high performance milling tool with integrated multi-sensor system.

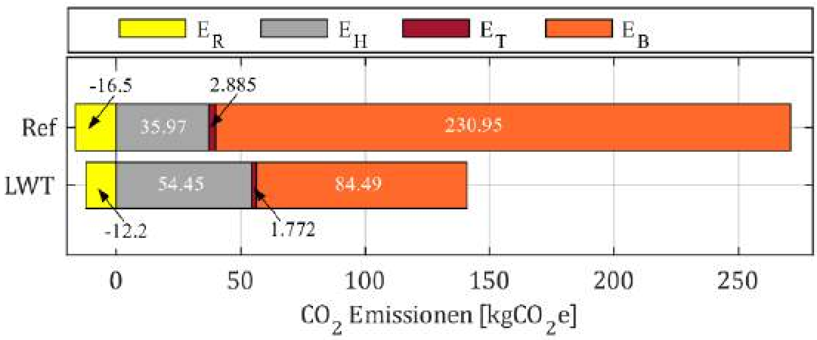

Figure 4: Comparison of CO2 emissions.

Regarding the improved performance and functionality of the innovative lightweight tool (LWT) an interesting question is, whether also an improved efficiency with respect to the overall CO_2 emission could be achieved. In order to answer this question, the new tool system is compared with the conventional reference tool by means of a balancing of CO_2 equivalents. For this, the manufacturing routes of both tools, the origin or fabrication (E_H) and delivery (E_T) of the materials as well as the emissions during the use phase (E_B) and those caused by recycling (E_R) are considered. Figure 4 shows a summary of the elaborated results. As can be seen, the newly developed system (LWT) shows a significantly improved efficiency compared to the conventional reference (Ref) tool.

4 Pre-stressed carbon-fiber reinforced polymer concrete in machine structures

Polymer concrete (also known as mineral cast) provides advantageous material properties with respect to damping (i.e. dynamic stiffness) and thermal stability compared to metal structures in machine tool elements [7]. Due to its lower density, in principle, even a lightweight design capability exists. However, because of its limited tensile strength, polymer concrete is hardly applied for moved machine components such as slides or traveling columns. The material is predominantly used in stationary machine beds and structures with more or less cubic geometries and shapes. In order to overcome the limitations of the tensile strength, pre-stressed carbon-fiber reinforced polymer concrete is investigated as a new class of materials for machine tool structures at the IfW [8,9] (Fig. 5). As visible in Fig. 5d, a significantly higher breaking load compared to pure polymer concrete can be achieved. This allows the realization of topology optimized components (Fig. 5a-c). Furthermore, sensory systems can easily be integrated into these structures during casting to realize 'feeling' components.

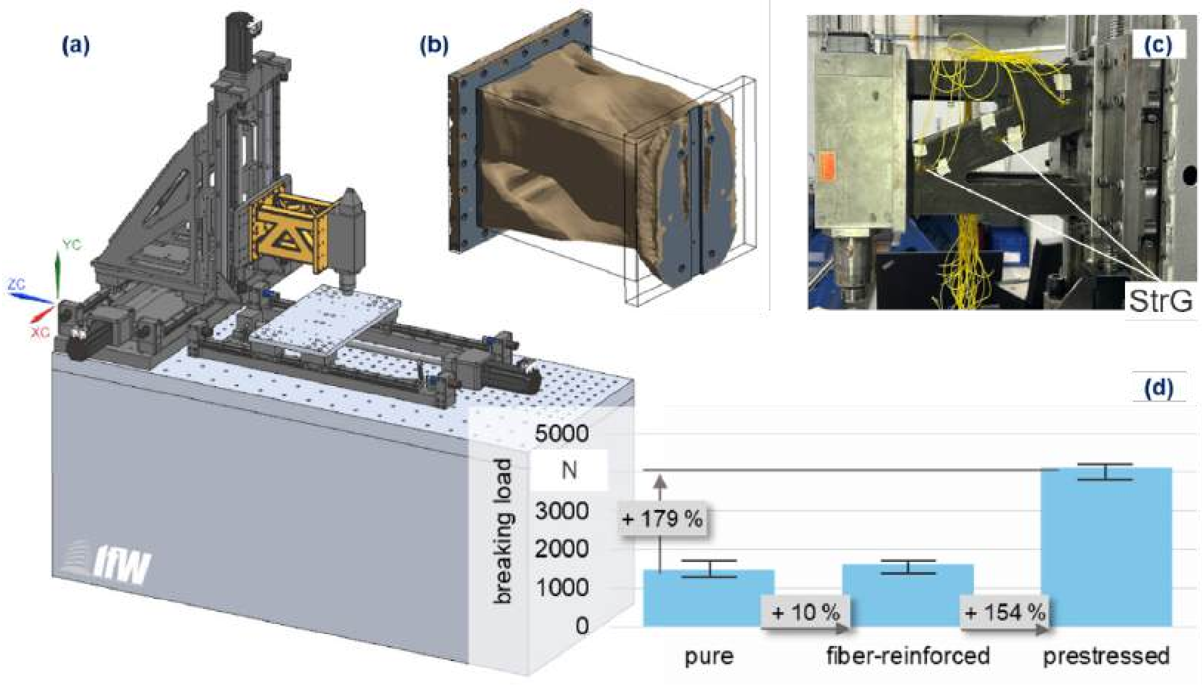

Figure 5: Pre-stressed carbon fiber reinforced polymer concrete for applications in machine tool structures.

Also for these developments, investigations regarding the CO_2 footprint were carried out [10]. Subject to the mass of integrated carbon fibers, and depending on the origin of the considered materials, advantageous CO_2 equivalents could be identified (Fig. 6), whereas the effects of the mass reduction and functional integration during the use phase could not be analyzed up to now.

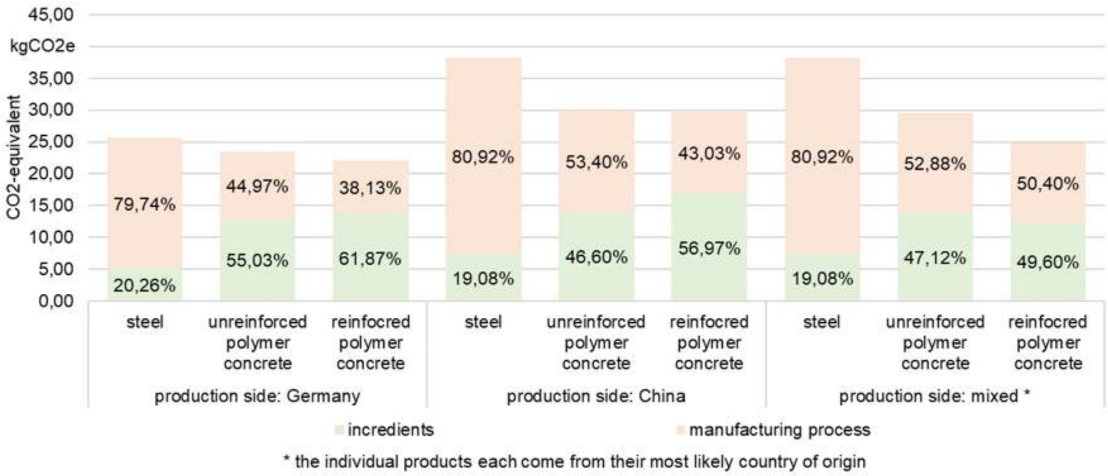

Figure 6: Comparison of CO2 equivalents.

5 Summary and outlook

This paper presents exemplary 'intelligent systems' for manufacturing applications and discusses their specific impact on the efficiency in production. In this regard, not only productivity, manufacturing quality and economic viability are considered, but also environmental aspects such as the CO_2 footprint are incorporated. It is shown that by means of innovative solutions, improved capability in terms of the production of lightweight products and the reduction of energy and resource consumption can be achieved. Furthermore, the presented investigations reveal, that decreased CO_2 equivalents can be gained. In future work, the environmental impact of innovative approaches will increasingly be incorporated in global optimization procedures. Though fundament balancing methods are already available, further work is necessary in order to provide the necessary calculation schemes and data platforms.

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Development of Process Chains, Integrating Wire Arc Additive Manufacturing, Multi-Axis Machining and Laser Hardening, for Low Series Parts Manufacturing

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Abstract

The manufacturing of parts usually requires a number of processing/machining steps. Especially for low series part manufacturing, the sequence planning of the various processes, within the process chain is a challenging task and is worth to study in detail. In this paper, the development of two possible process chains are described. First, a process chain for the manufacturing of (single piece) parts based on Wire Arc Additive Manufacturing (WAAM), followed by machining, is presented. It is shown that the quality of the WAAM part (as deposited) influences the milling process and vice versa. A second discussed process chain, focusing on the manufacturing of prototype parts, with hardened features, involves machining and selective laser hardening, both implemented on a single multi-axis machining center.

Keywords: Process chain development, Wire Arc Additive Manufacturing, Multi-axis machining, Selective laser hardening

1 Introduction

Low series or even single part production is challenging as the production of these parts often requires a number of machining steps. For low series production, additive manufacturing (AM) techniques are certainly appropriate processes, but for many AM processes the obtained surface quality and dimensional accuracy is not sufficient, making post-machining necessary. Another issue in low series part production is the inefficiency in the logistics process. In case, part features have to be hardened, the parts have to be unclamped after soft machining, transported to the hardening department for hardening, and consequently transported back to the machining shop, to be re-clamped and aligned for finishing, finally resulting in long throughput times. Given the above challenges, this paper discusses two manufacturing process chains, developed and investigated at KU Leuven. The first process chain is the combination of Wire Arc Additive Manufacturing (WAAM) and machining. The second process chain discussed in this paper is the integration of selective laser hardening within a multi-axis machining platform, making the manufacturing of hardened components possible within one clamping set-up.

2 Process chain development for Wire Arc Additive Manufacturing & machining

Wire Arc Additive Manufacturing (WAAM) is an additive manufacturing (AM) technique for the production of large and medium-size metal parts with medium geometrical complexity. The process uses an electric arc as a heat source to melt a metal wire and builds a component in a layer-by-layer manner. The surface quality obtained by WAAM is low (waviness around 500 µm [1]), leading to the necessity of further post-processing using conventional subtractive techniques, such as milling, turning, and grinding. In this section, the nexus between the as-deposited and post-machined surface quality is being studied. From a machining point of view, the initial state of the surface determines the variation in the chip thickness and the corresponding cutting forces.

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Inhomogeneous surface hardness, waviness, and low geometrical accuracy that cause the variation in cutting forces can also lead to the excitation of chatter vibrations of the system, including the workpiece, cutting tool, fixture, and CNC machine.

2.1 Experimental setup

Figure 8 shows the experimental setup for the “Wire Arc Additive Manufacturing – Machining” process chain, for which in this study the production of thin-walled components are being produced and investigated. The used WAAM setup is based on a six-axis industrial robot arm (CLOOS QRC320H). Parts are deposited using a Qineo pulse 450A welding power source with synergic control. A 1.2 mm diameter wire EN ISO 14341-A (G 42 4/M21 3Si1) was used as a filler material. The shielding gas was 85% Ar and 15% CO_2 mixture at a constant flow rate of 15 l/min. The distance between the contact tip and the workpiece was set to 15 mm and kept constant during the process. The thin-walled WAAM structures were deposited in a single-pass multi-layer manner. The dimension of the deposited parts was 45 mm x 100 mm (height x length). The wall width varied according to the welding parameters. The interpass temperature during the WAAM process was controlled using a FLIR A315 thermal IR camera (also depicted on Figure 8). Once the maximum temperature of the deposited upper layer had reached a specific value, the next pass was applied.

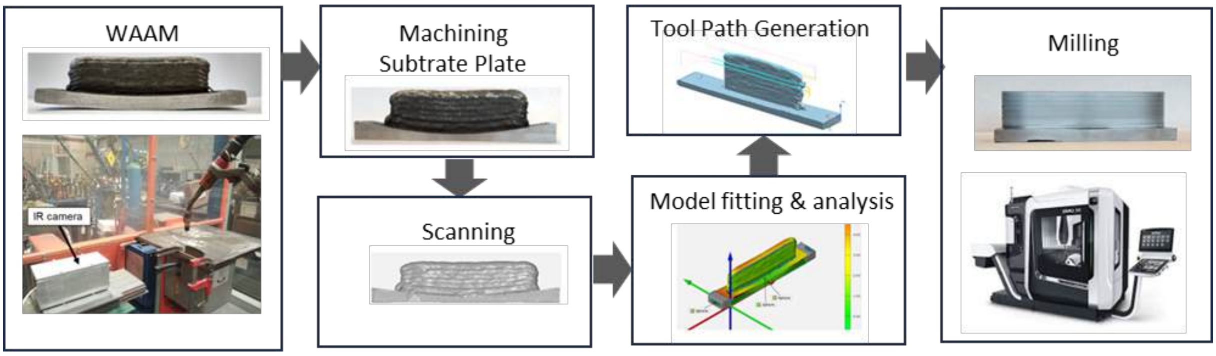

Figure 8: Process chain development for Wire Arc Additive Manufacturing (WAAM) and machining.

The heat input during the WAAM process introduces significant distortion of the base plate leading to poor clamping and low alignment accuracy on the CNC machine. To overcome these problems, the substrate plate was pre-machined from the bottom before scanning using an ATOS Compact 3D scanner. Subsequently, the CAD model of the final part was fitted within the scanned WAAM part, using GOM software. By comparison with an actual surface, the machining allowance was obtained, and part alignment was corrected when necessary. Additionally, flatness deviations (FD) of the as-deposited WAAM components were calculated based on the analysis of 3D scans.

Once the scanned WAAM part was aligned correctly with the reference CAD model, the maximal allowance to be removed was measured with respect to the middle plane of the reference part. Finally, the aligned scans were exported and used as a blank in the CAM software to program the required milling tool paths. The milling process was implemented on a DMG DMU 50 5-axis machine centre. The tool was a square shoulder end mill R390-016A16-11L (Sandvik) with exchangeable inserts [R390-11T3 08M-PM 4330 (carbide coated - CVD TiCN+Al2O3+TiN)], diameter 16 mm, helix angle 15° and two teeth. Milling of the samples was implemented in two steps: (i) face milling of the top surface of the WAAM component to provide accurate values of axial depth of cut during the side milling and to remove the upper zone, which is characterized by the higher hardness values (ii) side milling using cutting order 'level first' (in case of multiple numbers of cuts). The down-milling strategy that is recommended for the machining of carbon steels was applied. To evacuate the chips from the cutting zone, compressed air was used during machining (i.e., dry cutting was performed), as dry cutting was recommended by the tool manufacturer.

2.2 Interaction between WAAM and machining

The primary constituent unit of the WAAM process is the weld bead (Figure 9a), which is strongly dependent on heat input. Further, the geometry of the weld bead determines the lateral surface modulation. The raw WAAM surface with the original width (total wall width, TWW) is machined to the effective wall width (EWW). As a result, the total allowance depends on the WAAM parameters and could not be controlled separately.

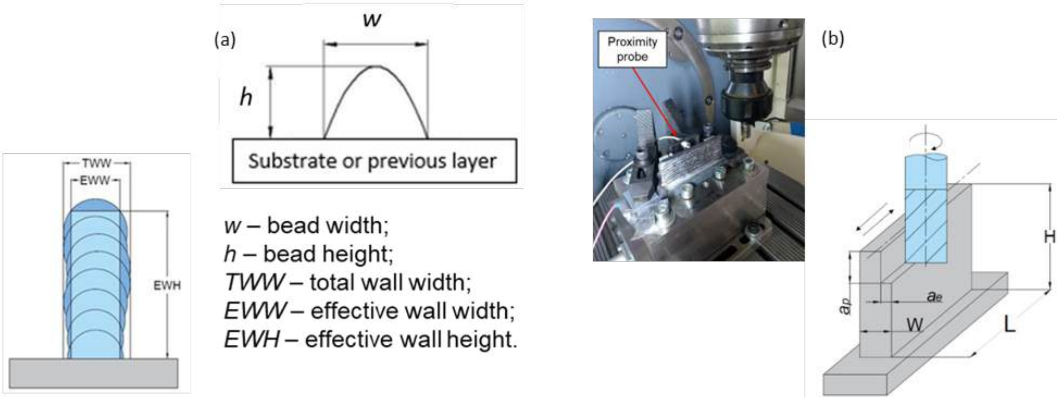

Figure 9: Representation of weld bead geometry and the machining process setup.

Definitive Screening Design (DSD) was used as a 'design of experiment' to determine the welding and milling parameters' collective impact. Investigated welding process parameters were wire feed speed WFS, travel speed of the WAAM robot TS, and interpass temperature IT. The investigated parameters for the milling process, were cutting velocity v_c, feed per tooth f_z, axial depth of cut a_p, and the number of passes n. The number of passes is used instead of the radial depth of cut a_e due to the WAAM components' characteristics. The total wall width (TWW) and effective wall width (EWW) of the WAAM components depend on the WAAM parameters. The total allowance to be removed per side also depends on the WAAM parameters and could not be controlled separately. By setting the number of passes, the radial depth of cut for a specific pass is determined as the total allowance to be removed divided by n.

The WAAM parameters determine the mechanism responsible for the weld bead formation and shape of the bead cross-section. The surface obtained after the deposition is characterized by the flatness deviation, which is a quantification of geometric quality. In addition, the machined surface quality results from the machining parameters and the quality of the as-deposited surface. Figure 10 shows the impact of the cooling time (($\Delta t8/5$ represents the cooling time from 800°C to 500°C) on the hardness, flatness deviation and the surface roughness. It shows that a rise of cooling time leads to an increase in surface roughness of the machined WAAM surfaces. This is due to (1) increase in as-deposited flatness deviation resulting in variation of radial depth of cut, thus the variation of cutting forces and (2) reduction of hardness that has a negative impact on the chip formation during milling. Nevertheless, four samples with significantly higher surface roughness were observed, as highlighted in Figure 10b. For these samples, increased roughness was caused by the instability of the milling process.

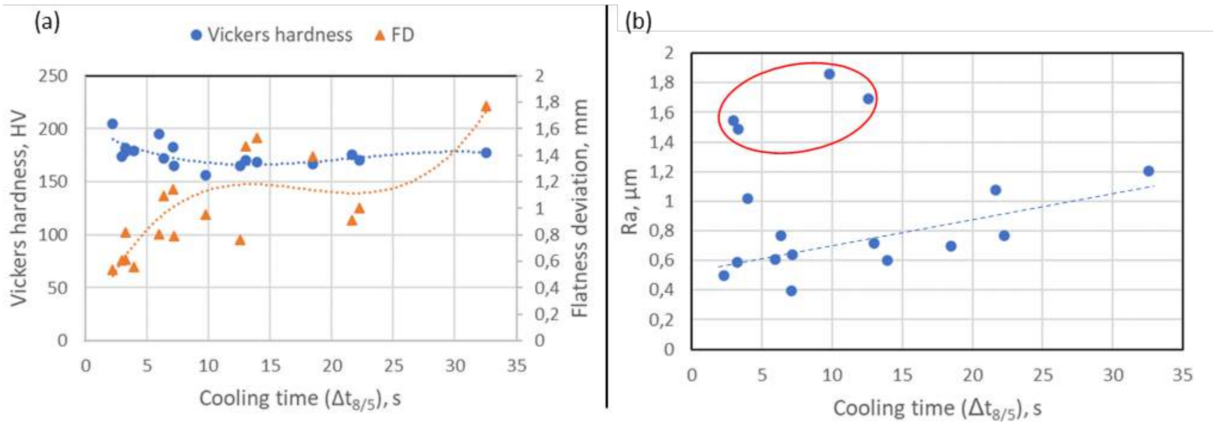

Figure 10: Impact of cooling time ($\Delta t_{8/5}$) on (a) the hardness and flatness and (b) the roughness of machined WAAM surfaces.

Figure 11 shows additional results of the impact of welding and milling parameters on the surface finish of machined WAAM surfaces. An increase in the cutting speed makes the surface smooth (Figure 11a), except in the case of the large axial depth of cut (a_p). The change in a_p is related to the stability of the milling process. The cutting system becomes unstable, and chatter develops when the axial depth of cut exceeds a limit for a given cutting speed and width of cut. The impact of the increase in a_p is explicitly visible in Figure 11b, where the large value of a_p results in a rough surface after machining. The number of passes impacts the surface finish (Figure 11c) as it determines the radial depth of cut; a_e = (TWW - EWW) / (2n). In conjunction with the machining parameters, the initial state of the surface influences the final roughness. For example, even at a larger a_p, a hard surface machining leads to a smooth surface (Figure 11d). It is well known that increased material hardness leads to reduced built-up edge height and change in the mechanism responsible for built-up edge break-off and retraction during machining of carbon steels. As a result, the final surface finish and tool life improve. The TWW offers stiffness to the wall; therefore, a thin-wall structure leads to a rough finish (Figure 11e), irrespective of radial depth of cut controlled by n. In extreme conditions (n=1), even thick wall machining results in a rough surface, as shown in Figure 11e. The flatness deviation effect is difficult to isolate in this investigation as it is coupled with the TWW, as explained earlier. The impact of the surface modulation is eclipsed behind the effect of the TWW; however, a small value of the flatness deviation at a higher value of axial depth of cut results in an increment in surface roughness (Figure 11f). A high a_p value combined with small TWW could lead to the excitation of chatter vibration during milling resulting in significantly higher roughness for four samples (Figure 10). Thus, the impact of milling dynamics should also be considered.

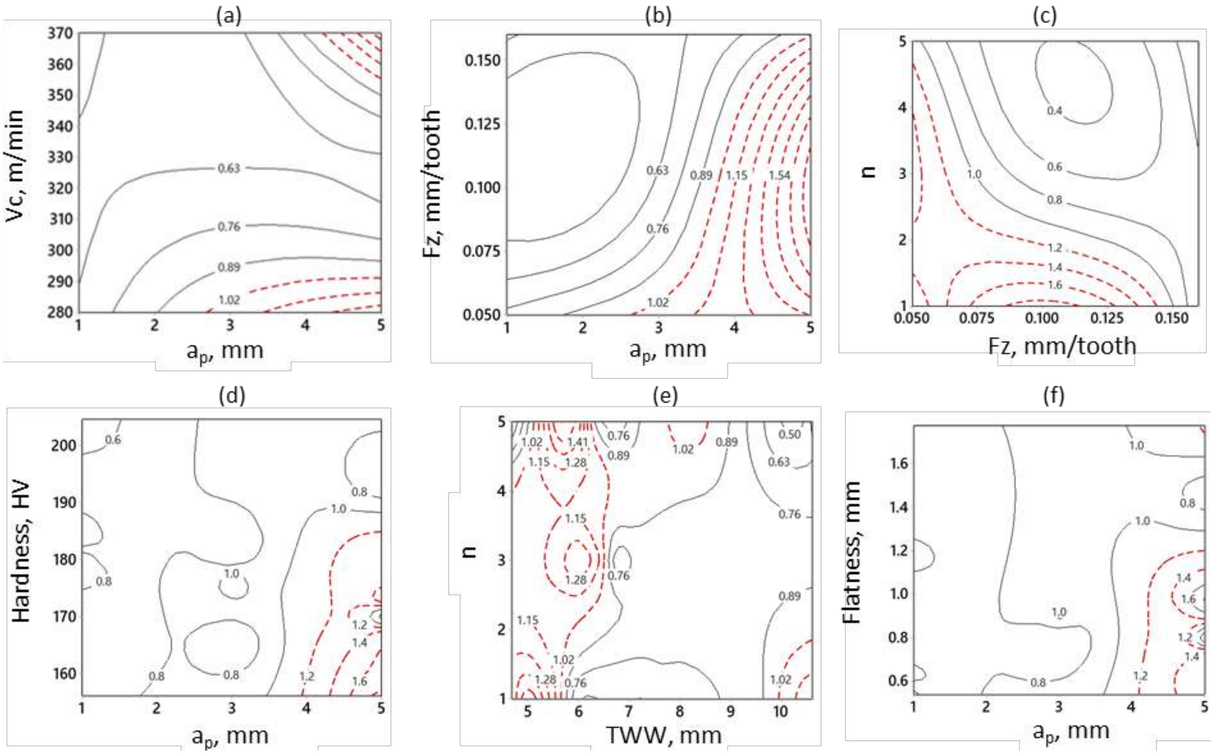

Figure 11: Impact of welding and milling parameters on the surface finish of machined WAAM surfaces (----- Ra > 1 µm, ──Ra < 1 µm).

3 Process chain development for Machining with Integrated Laser hardening

Integrating the hardening operation within one machining platform greatly reduces the through put time, especially for parts productions in low series. Additionally, laser hardening is a selective operation, which only heats up the workpiece locally, making a local quenching by the base material possible, avoiding large deformations, even resulting in a minimum number (often none) of hard finishing operations [2]. The potential of this process chain is illustrated by the manufacturing of a single piece "prototype" gear, made of C45 steel (Figure 12b), with a diameter of 98 mm and a thickness of 16 mm.

3.1 Experimental setup

To investigate the process chain of machining with integrated laser hardening, a self-developed laser system has been integrated into the DMG MORI NTX2000 Mill turn center (Figure 12a). This is achieved by the use of a laser head which can be picked up as a normal tool, using a Capto tool holder. The laser source used is a 500 W High Power Diode Laser (HPDL) with a wavelength of 940 nm. The development of the system, based on the use of a laser scanning head, has been discussed in other papers [3]. By using a high-frequency scanning mirror, integrated into the tool head, hardening tracks up to a width of 30 mm can be performed. Machining strategies [] can be applied to perform the machining of the gear in unhardened state. The chemical composition of the investigated gear is: 0.43% C,0.4% Si, 0.4% Mn, 0.045% P, 0.045%S, 0.4% Cr, and 0.045% Mo..

3.2 Selective laser hardening strategy

After machining, a selective laser hardening operation is performed. During laser hardening of the flanks, the laser light has to stay in focus over the entire profile of the gear tooth. To achieve this, a laser programming software, developed within this research, outputs a NC code for the DMG MORI NTX2000. The programming software uses a 2D contour of the gear to calculate the corresponding X-axis value (up and down motion of laser head) and C-axis value (rotation of the spindle), keeping the laser head in focus while the spindle of the machine rotates the gear. This programming software allows the user to select certain sections of the gear to be hardened. The user can also select if the gear has to rotate in a clockwise or counterclockwise manner or if the tooth flanks are hardened from the top to the root or vice-versa.

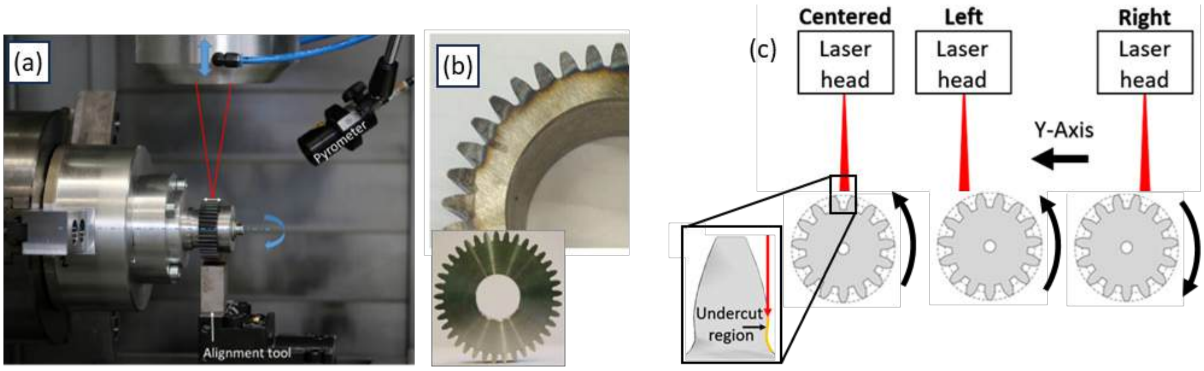

Figure 12: Integration of a laser hardening tool within a DMG MORI NTX2000 machining center (a), gear part (b), and laser beam positioning (c).

Due to the profile of a tooth flank, the angle of incidence of the laser light changes during laser hardening, resulting in changes of the absorbed laser power. This change can influence the quality and hardening depth of the hardened layer. To compensate for this absorption change a feed-forward power regulation function is implemented. A simplified laser hardening model was implemented into the programming software which calculates a feed-forward power diagram based on the laser absorption curve, the estimated energy density required for hardening, scanning frequency, scanning width and the angle of incidence of the selected hardening zones. This information, outputted as power output correlated to certain axis positions, is loaded into the laser head controller, a National Instrument Single Board Rio (NI SBrio). The NI SBrio, reads in the locations of all machine axes, and applies the specified power output to these corresponding axis positions.

In combination with this feed-forward power control, a feed-backward control system was implemented to control the surface temperature during laser hardening. The feedback control system consists of a two-color Dr. Mergenthaler pyrometer (Figure 12a) and logs (at an update of 0.1 ms) the actual temperature of the surface of the workpiece in a circular region of maximum 17 mm diameter. Filtered data obtained by the pyrometer is used in a feedback control loop (PID) to control the surface temperature to a predefined set-point. Case by case, the user can decide to use the controlling options (feed-forward or feed-backward) separately or to combine them. If the combination of both controlling systems is used, the feedback control system will regulate the surface temperature to the requested set-point starting from the laser power output by feed-forward power regulation. This prevents power peaks at the start of a hardening track.

3.3 Discussion

First trials to harden the flanks of the gear showed that it is impossible to heat treat the undercut region of the gear flanks (indicated in orange on Figure 12c). A centered position of the laser head (in the center of the spindle axes) does not allow the laser spot to reach this region, making it impossible to harden that particular area. This has been solved moving the laser head (Y-axis, out of center) and an additional spindle rotation obtaining a more uniform laser beam incidence. A laser move offset from the center of 12 mm (Y direction), with feed-forward power regulation combined with feed-backward control, reached the best results. The resulting optimal parameters set used as starting parameters were: energy density of 500 W/cm^2, scanning frequency 25 Hz, scanning width (16mm = gear width), feed rate of 220 mm/min. The programming software estimated the variation of required applied laser power over the profile of the gear tooth between 420 W and 490 W. For the feed-backward control, a set-point of 1250 °C was used. Results showed that a uniform hardened layer, with a maximum hardness of 645 HV at the surface and a hardness of 551 HV at a depth of 113 µm, was formed across the profile and flank profile of the gear tooth (Figure 13a). Essential for reaching a uniform hardening of the tooth flanks is to apply a top-down strategy (as applied in Figure 13a), where the laser scan moves from the top circle down to the root circle. If a bottom-up strategy is used (laser moves from the root to the top circle) (Figure 13b), heat is accumulated in the top of the tooth resulting in annealing of the opposing tooth flank that was hardened before. The hardness measured at the annealed side dropped to an average of 400 HV. The obtained hardening depth is thus around 115 µm, which was a maximum for the used set-up.

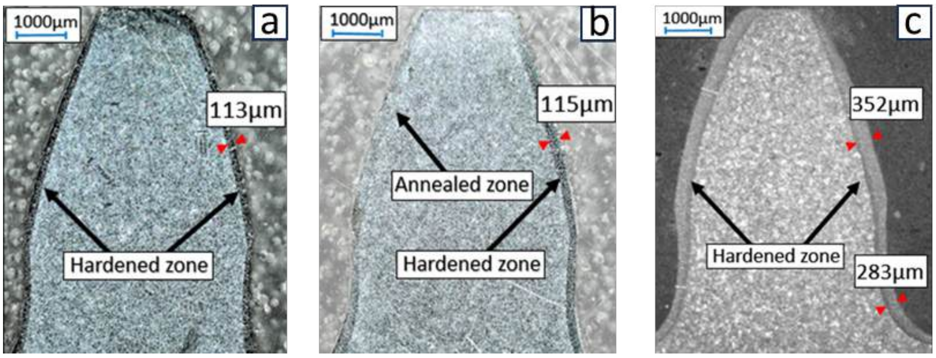

Figure 13: Hardened zone: (a) bottom-up strategy, **(**b), top-down strategy, (c) high power density.

According to gear manufacturers, a higher hardening depth of at least 140µm or higher should however be obtained. By using the set-up, but by limiting the scanning width to for example 7mm (not the whole flank width was then hardened) and using the following process parameters: top-down strategy, feed rate: 500 mm/min, scanning frequency: 50 Hz, laser power: 500 W, a maximum hardening depth of 352 µm (526 HV) (Figure 13c) was reached. Reducing the scanning width was necessary to gain sufficient power density to obtain hardening with these high feed rates. On the other hand, reducing the federate was not an option, as it again resulted in an annealing effect of the other side of the tool flank.

4 Summary

This paper described the development and investigation of two process chains, focusing on the manufacturing of parts in low series. It is shown that in the process combination of Wire Arc Additive Manufacturing, followed by machining, that the quality of the as deposited part, influences succeeding machining process and the resulting surface quality. Therefore, the process parameters of both processes should be controlled in a combined way. A prototype gear part has been used to investigate and demonstrate the potential of machining and selective laser hardening, integrated on a single multi-axis machining platform. Through the implementation of a feed-forward and feed-backward power control, combined with a correct laser moving strategy, uniform hardening depths on the flanks of the tested gear could be reached.

5 Acknowledgements

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DATA DRIVEN MANUFACTURING

"Without data, you're just another person with an opinion."

— W. Edwards Deming

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Shared Data Ecosystems - Enabler for a Green Production

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Keywords: Carbon Footprint Forecasting, Federated Data Exchange, CO_2 Emissions Reduction, Sustainable Product Development, Data Privacy in Supply Chains

1 Extended Abstract

The EU's goal of climate neutrality by 2050 and a 55% emissions reduction by 2030 requires a reevaluation of industrial processes. In 2023, the industrial sector was responsible for about 24% of Germany's greenhouse gas emissions [1]. Additionally, regulations like the Corporate Sustainability Reporting Directive (CSRD) require companies to identify and implement emission reduction measures. To achieve climate neutrality, the carbon footprint of products is crucial for tracking emissions and identifying savings. Quantifying CO_2 emissions provides companies with transparency and a basis for reducing their environmental impact. Up to 80% of a product's carbon footprint is influenced by decisions made during product development [2]. In the following, we present our results from the Gaia-X lighthouse project EuProGigant. We show how shared data ecosystems enable a greener production by illustrating the exemplary use case of stakeholders in manufacturing data ecosystems that use trustworthy data exchange to forecast product carbon footprints and develop low CO_2 emission products [3].

A data ecosystem for manufacturing involves shared digital activities and resources that enable new industrial value creation among data owners, providers, and users. When data is selectively and securely shared in line with privacy laws, this orchestrated exchange can generate additional value and synergies among stakeholders. Federated data exchange models enhance manufacturing processes by enabling secondary data use, creating opportunities for extra revenue as well as cost and CO_2 emission savings. For companies, this means accessing valuable data without bearing all costs alone, improving innovation, competitiveness, and growth.

As part of the EuProGigant project, the presented use case analyzes the value chain of components to enable federated data value creation across company boundaries. Since no physical component exists during the product planning phase, the use case extends beyond calculating the product-specific carbon footprint to include forecasting potential emissions during the product's lifecycle, depending on the production scenario. This approach aims to enhance decision-making with measurable indicators of ecological sustainability. Therefore, we are developing a carbon footprint forecasting service, included in the EuProGigant dataspace, that can be utilized by product development staff. We developed the forecasting model as a prototype for injection molded parts and plan to expand the service to include other manufacturing processes in the future.

The carbon footprint forecasting service is delivered via a web application where users input data about a hypothetical production scenario, such as quantity and material composition. The service facilitates data transfer and queries with injection molding companies, calculates the carbon footprint and energy consumption of the scenario, and provides comparative results. It uses both database and real shop floor data to estimate emissions, including indirect ones, helping users make informed decisions in product development since accounting for emissions still presents challenges for many manufacturing companies.

Calculating the projected footprint for production scenarios requires data transfer across the supply chain. This demands an interoperable system and raises privacy concerns, as CO_2 data can reveal sensitive information.

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Companies may be reluctant to share such data without contractual safeguards due to fears of losing competitive advantage. The EuProGigant shared data ecosystem solves this problem by allowing companies to share the needed data while considering data privacy criteria. Data will remain with their owners until a usage agreement is signed. This concept can be applied across industries to optimize CO_2 emissions in product.

Besides forecasting the product carbon footprint, the exchanged data could also be utilized for corporate sustainability reports and populating the Digital Product Passport with CO_2 emission information. This data can help lower the carbon footprint of not just individual products, but entire industries, thus supporting the goal of achieving climate-neutral production. The approach can be applied across various industries beyond injection molding and plastics, offering a wide range of potential applications. Data ecosystems become enablers for green production, not only by providing services but also by allowing users to market their data to other players, enabling them to develop, enhance, or test their own applications, further driving sustainability.

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Twin Transition in Manufacturing
Chapter: Data Driven Manufacturing

An Auditable PPR Framework for the Digital Product Passport using AAS-based Process Passports

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Abstract

Starting with 2027, the first product groups in the EU are legally bound to introduce the Digital Product Passport (DPP) as an enabler for circular economy by sharing product-related information along the entire life cycle. While the DPP also provides new business opportunities through data transparency, companies face uncertainties regarding design, setup, operation and maintenance of the required IT infrastructure, and securing their business secrets. In this paper, a framework for the DPP is presented, enabling detailed traceability of individual processes, and recalculation, verification and extension of DPP key performance indicators (KPIs) in case of audits or changing DPP requirements. Through referencing between products and processes within the Asset Administration Shell (AAS), a verifiable DPP is envisioned, facilitating services like accountability for green audits and aggregation for a comprehensive Life Cycle Assessment (LCA). Finally, the framework is applied in a case study within tool manufacturing for the calculation of the Product Carbon Footprint (PCF).

Keywords: Digital Product Passport, Asset Administration Shell, Product Carbon Footprint, Data Space, Ecosystem

1 Introduction

Manufacturing Industry is challenged by the Green Deal to enable circular economy by sharing product-related information through the Digital Product Passport (DPP) along the entire value chain [1]. While the DPP enables new business opportunities, sharing data within competitive markets, such as in the manufacturing industry, is often risky. This leads to uncertainty among companies, and a struggle on setting the right course between data transparency in the value chain and securing their own digital sovereignty, without providing too detailed insights into core competencies and business secrets. Initiatives like Catena-X and International Manufacturing-X are set on enabling collaboration in value creation networks using data space and data and service ecosystem technology, and must therefore address a common trust plane, e.g. Gaia-X, for transparency and sovereignty of data in the value chain. To enable the DPP, Pellegrini et al. [2] identified four major fields of challenges: (1) Product ID, (2) Product Data Carrier, (3) Digital Connector, and (4) IT Architecture, with the latter two requiring companies to operate an IT system capable of identifying, locating, storing, sharing and managing interoperable data and data access along the product life cycle. This further introduces the challenge of collecting, preparing and computing data into required information and key performance indicators, and the requirement of employing trained IT personnel or paying external services to setup, operate, and maintain such an infrastructure. For companies, the environment remains uncertain, due to lacking mature and out-of-the-box technologies for sovereign collaboration in data spaces and ecosystems, as well as software modules for dynamically building DPPs from aggregated manufacturing data. Schaltegger and Burritt [3] mention, that there exist limited methods for systematically organizing the collection and sharing of environmental data within

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companies. Furthermore, the built DPP is required to enable detailed traceability along the value chain, and possible verification or investigation of non-conformance of product or even process data by auditors. Therefore, the objective of this work is to develop an auditable and scalable DPP framework that ensures data sovereignty and introduces the Digital Process Passport (DPssP) to provide detailed insights. The framework is applied in a case study for the modelling of products and processes involved in the manufacturing life cycle stage of an injection moulded product, including the calculation of the Product Carbon Footprint (PCF) of injection mould manufacturing as a crucial early step in the value chain of injection moulded products. During the injection moulding process, the injection mould precisely shapes the injected plastic, ensuring the final product conforms to specifications and tolerances.

2 Literature review

The DPP serves as key enabler on the path to a circular economy by facilitating the collection, storage, and retrieval of relevant information throughout a product's entire life cycle. The DPP will be mandatory for products sold in the EU, with the first the product groups (e.g., batteries) starting in 2027, and is incorporated in the Ecodesign for Sustainable Products Regulation (ESPR) [1], which came into effect in July 2024.

The Asset Administration Shell (AAS) is a fundamental concept driving digital transformation across industrial organizations, also identified by Pellegrini et al. [2] to be a core contributor to advancing the DPP. By using the AAS framework a standardized digital representation for an asset can be obtained. An asset is defined as a physical or logical object that is owned or under the custody of an organization and provides either a perceived or an actual value to the organization [4]. An AAS is composed of a header and a body. The header includes details about the AAS and the asset it represents, while the body contains one or more submodels. Garrels et al. [5] mention, that these submodels can be used to implement different sections of the DPP, while AAS submodel elements are used to implement the individual data elements within each DPP section. Neligan et al. [6] design the DPP comprising of three submodels for identification, description and characteristics and environmentally relevant information with the latter including data on the carbon footprint. The primary objective of conducting a carbon footprint is to calculate a product's potential contribution to global warming, expressed as CO_2e, by quantifying all significant GHG emissions and removals throughout the product's life cycle or selected processes, in accordance with cut-off criteria [7]. A Carbon Footprint submodel template [8] provided by the Industrial Digital Twin Association (IDTA) facilitates the exchange of an asset's carbon footprint along the value chain and supports multiple PCF values using various calculation methods and assumptions. The German Electro and Digital Industry Association (ZVEI) [9] demonstrates the dynamic calculation of the PCF for a control cabinet, using the AAS to facilitate the exchange of sustainability information among business partners within a value network. As, to fully utilize the capabilities of the AAS and to effectively implement the circular economy, it's essential to consider all stages of the life cycle and involve relevant stakeholders, Pourjafarian et al. [10] emphasize a multi-stakeholder approach to both the AAS and the DPP. Plociennik et al. [11] demonstrated for the sorting of electronic waste, in the end-of-life stage, that the DPP can be expanded by allowing stakeholders at every stage of the life cycle to both access and contribute content.

While the aim of the DPP is to facilitate easier digital access to essential product-specific data concerning sustainability, circularity and regulatory compliance, the DPP is not designed as a tracking and tracing tool but can incorporate traceability data when relevant [12]. Alt et al. [13] argue, that the DPPs product-centric approach limits its applicability, and in addition to the DPP, address a concept for a DPssP, which provides more detailed traceability of the individual processes. The concept of a DPssP builds upon the idea of a DPP but focuses on documenting and tracking the processes involved in creating, manufacturing, distributing and disposing of a product. In comparison to the DPP, DPssP is oriented more towards internal company processes and is geared towards enhancing process optimization and driving continuous improvement initiatives rather than catering primarily to consumer needs. A holistic DPP requires data and information from every step of the product's production process [14]. The DPssP is expected to determine energy consumption and CO_2 emissions on a process-specific level. Given its close connection with the DPP, their integration across the entire product supply chain is both feasible and advantageous.

3 Design of an auditable DPP Framework using DPssP

This work presents an auditable framework for the DPP, enabling detailed traceability of individual processes to enable comprehensive verification of process data, and thereby providing concepts for designing future-proof IT architectures for the DPP. As auditing is not only product-, but also process-related, it involves not only the product and its materials, but also the context of production, like machinery and environmental conditions. Therefore, the use of DPssP plays a key role in this framework, by combining a Product-Process-Resource (PPR) approach with the DPP and the AAS. Figure 1 shows the relationship graph between Digital Product and Process Passports, with resource being a specialization of product, e.g. a machine or manufacturing utility, that may be used in a manufacturing process to produce a product without being completely consumed by or installed in the resulting product.

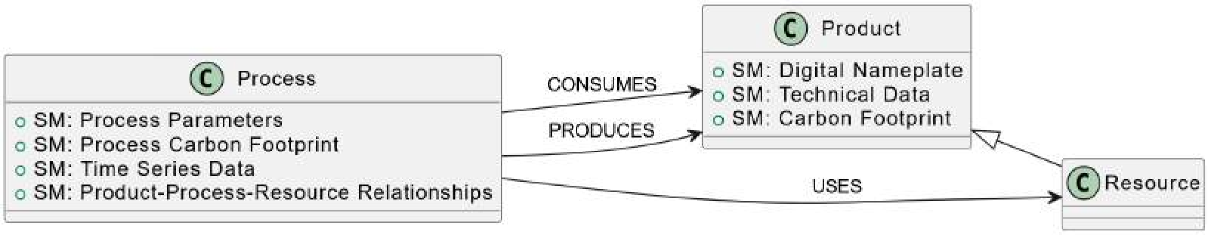

Figure 1: Diagram of the high-level Product-Process-Resource (PPR) model, including the relevant submodels for the AAS of the Digital Product and Process Passports, and their relationships.

The DPP is also similarly applied for resources as for products with the following submodels used: Digital Nameplate [15], Technical Data [16] and Carbon Footprint [8]. Other submodels may also be present depending on the application. The DPssP is dependent on the type of process and the relevant data associated. Next to the Time Series Data [17] submodel, the Process Carbon Footprint contains process key performance indicators (KPI) relevant for the calculation of the PCF of the respective process. These may be aggregations of collected timeseries data like electrical energy consumption as integration of measured electrical power values. The key of the DPssP is the Product-Process-Resource Relationships submodel, that is describing the relevant one-to-many relationships between the process and the respective products and resources using the Hierarchical Structures enabling Bills of Material submodel [18] provided by the IDTA. This is following a top-down approach, describing the relationship to other assets by referencing the global asset ID. As a result, the life cycle of products, including their manufacturing processes, and referenced resources involved in manufacturing, can be represented as a graph using a set of AASs. This provides the basis for calculation of a PCF from the properties provided in the different life cycle phases within the PPR graph, or for calculation and aggregation into a comprehensive Life Cycle Assessment (LCA), if all relevant data is available.

To integrate and operate the above-mentioned DPP framework certain aspects in the IT architecture must be considered: **(1) a data acquisition system** is employed, especially with a focus on tracking relevant data for CO2e emissions. Industrial grade solutions may use Supervisory Control and Data Acquisition (SCADA) systems. Al Assadi et al. [19] demonstrate an automated environmental impact assessment using MQTT protocol as a basis for tracking energy usage and CO2e emissions via AAS. Ajdinović et al. [20] also show that event-sourcing can be used to capture and store process data in AASs. They further show that **(2) data aggregation capabilities** are necessary in an IT system to dynamically generate the relevant data (e.g. electrical energy from power measurements) for the DPP, or accordingly the DPssP proposed in this work. As storing and querying multiple interconnected AASs efficiently at large scale is currently problematic, a **(3) data storage and management** system is useful, either for storing or indexing data. With the overall PPR model representing a graph, graph database technology is feasible for handling the complexity of the references between the assets, while also SQL, or NoSQL databases are applicable. The system must ensure the PPR graph is easily accessible and manageable for subsequent querying and computation. While the format for backend data storage may be different from the AAS syntax, the **(4) integration of life-cycle data** is essential for ensuring that all life cycle stages can be linked. This involves providing capabilities of importing, exporting one or multiple assets with its relationships as AAS or Composite AAS, which encapsulates the graph. They must dynamically generate AASs from the storage system to conform to Type 1 or Type 2 AAS. Additionally, **(5) querying and computation** of e.g. the PCF in the PPR graph must be efficient and simple to use. Further, **(6) data security and access control** are crucial when interacting with other external participants, as process data contains sensitive information. Ecosystems, data spaces and their connectors as well as Composite AAS must ensure data sovereignty by implementing strong access mechanisms, including authentication and authorization based on a combination of attributes, roles, and policies. Whereby an attribute may be any element of an AAS submodel or a context depended input like a verifiable credential and the policies may be internal or context depended and relying on any combination of the attributes. The access control can be extended with technologies like Compute-to-Data, Selective Disclosure, and Zero-Knowledge Proofs (ZKP) to protect data while enabling secure computation. Finally, **(7) auditability** must be supported. This allows verification of process data, e.g. timeseries, or files, such as images. Here, too, a distinction between extern and internal company boundaries must be made. Externally Blockchain anchoring technology for traceability, possibly combined with file pinning for transparency, or ZKP for long living independent verification possibilities may be employed where trust is an issue, providing transparent and verifiable records of data and transactions. Internally the processes of import, export, aggregation and transformation of data related to DPssP must be auditable.

4 Case study

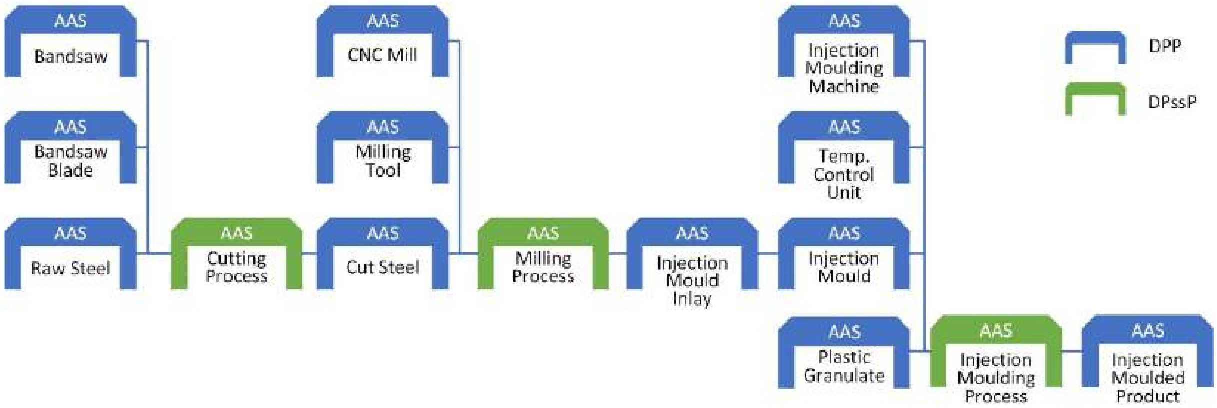

Figure 2: AAS-based Digital Product and Process Passports in a cradle-to-gate life cycle in injection moulding

The case study presented in Figure 2 outlines the value chain from tool steel to the final injection moulded product, with a focus on a single inlay of an injection moulding tool. A component is cut from tool steel using a band sawing machine and then machined in a CNC milling machine. The inlay is installed in an existing injection mould, and the injection moulding process is carried out. All the products, processes, and resources detailed in the use case are represented as either physical or logical assets using the AAS.

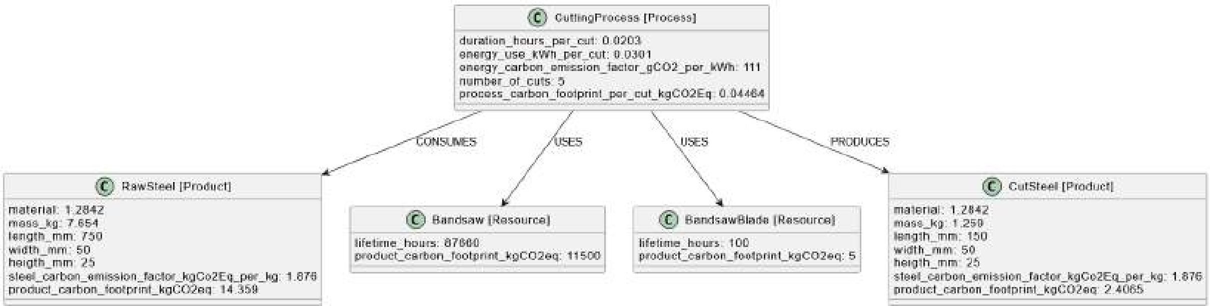

Figure 3: Digital Product and Process Passports (simplified for usability and readability) with relevant data for PCF calculation for the first Process Passport (CuttingProcess) within the life cycle presented in Figure 2.

The first part of this life cycle regarding an automated band sawing process is shown in detail in Figure 3. The process data shown is resulting as KPIs for duration per cut, energy per cut and number of cuts (Process Parameters submodel) from timeseries data collected from a power meter during the process (Time Series Data submodel) and calculated for the PCF per cut (Process Carbon Footprint submodel).

As a designated query language for the AAS does not exist yet, for the calculation of the total PCF for a product the relevant properties must either be extracted individually, or the AAS syntax translated into Resource Description Framework (RDF), to use SPARQL for graph queries. Nevertheless, this is currently not a straightforward task, as SPARQL queries within the AAS can quickly become complex, when having to query relationships between multiple assets through the PPR Relationship submodel, e.g. in a composite AAS, that is including the whole graph.

Currently having a combined approach of recursively extracting properties and importing into a flat and easy to query property graph seems reasonable for the application of PCF calculation, while e.g. making use of the modelled semantics would make a sophisticated approach. For comparison, ZVEI [9] use a variable called “Footprint Information Combination” to already aggregate the PCF values for subcomponents of a control cabinet, to enhance usability. Therefore, in this case study, the submodel properties are recursively extracted into a flattened property graph, and imported into a neo4j graph database, omitting unnecessary data points for readability. The database could then be used to calculate the Process Carbon Footprint and the Product Carbon Footprint in a single graph query.

5 Conclusion

This work presented a first step into an auditable DPP framework, by extending the DPP with the DPssP and discussing a suitable IT architecture. Auditing is becoming especially more relevant in the future with the environmental, social, and governance (ESG) framework receiving more attention. The Digital Process Passport offers great potential by providing detailed information, making it useful for proving compliance within ecosystems. Additionally, exploring the use of ZKP in combination with the DPP could strengthen the framework. Future work should focus on improving the IT architecture around the framework regarding its application in ecosystems, using Compute-to-data, Selective Disclosure and ZKP, and enabling automated auditing.

6 Acknowledgements

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Pre-Validation and Optimization of Intralogistics Systems in Development Using High-Fidelity Discrete Event Simulations

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Abstract

Discrete Event Simulation models are widely spread tools to represent intralogistics systems and to optimize their designs. To ensure reliable model behaviour, validation using real-world data is a common method. However, validating models representing not yet existing systems becomes challenging due to the lack of these data. This paper proposes a method to pre-validate a new DES-model representing a system in development. To pre-validate this new model, another simulation model is validated. Since both models share the same software components, process flows and logics, pre-validation of the new model is achieved based on validation of the other model. Furthermore, optimization aimed at reducing resources is analysed: In this evaluation the system's customer throughput with reduced personnel is compared to a reference with standard staffing. Simulation results are compared using the Kolmogorov-Smirnov test, suggesting the system with reduced personnel can achieve the same throughput as the reference system with standard staffing.

Keywords: Discrete Event Simulation, FlexSim®, Intralogistics Systems, Optimization, Validation

1 Introduction

Discrete Event Simulation (DES)-models consist of logical components, which are defined by status, events and activities, while resources and entities, define their physical components [1]. Due to these components, DES-models are suitable to mirror and represent systems that can be described by sequences of events and changes of status, e.g. in processes of manufacturing systems, logistics systems or in the healthcare sector [2-4]. They are commonly used to analyse items and people flows, to highlight bottle necks in systems and for planning of resource capacities [4].

The development of complex systems benefits from designing simulation models [5,6]. They enable to perform experiments in the simulation model's virtual environment before the real-world system even exists [7]. Sensitivity analyses can be performed to evaluate and compare different system designs and allow the implementation of optimization measures [8,9]. This reduces the need to modify, rebuild, or risk damaging physical systems. Moreover, performing these experiments in a virtual environment saves time and resources compared to physical testing [7]. Furthermore, DES-models can be used to forecast system behaviours allowing fast decision-making processes to bring the system to market [3,10]. However, validation of the model is crucial to ensure the simulation model's accuracy [6].

The design of a physical system, yet to be built, is influenced by the simulation model's results. Therefore, reliable simulation results are essential. Conducting a reliable validation process for such simulation models is challenging since there is no real-world data to compare the simulation results with. To address this issue, this paper

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proposes a pre-validation process of a new simulation model, representing a not yet existing intralogistics system, with the help of another simulation model, which mirrors an existing, physical state-of-the-art system.

The paper is structured as followed: In section 2 related work is presented, concerning methods of validating simulation models. Section 3 states this paper's research method, section 4 describes the use case and in section 5 results are discussed. Section 6 sums up the results and states the limitations of the proposed method.

2 Related Work

Statistical tests and mathematical methods can be used for validation procedures, e.g. testing if data sets may originate from the same distribution function [11,12]. Using these tests and methods, the reference values, with which the simulation results are compared to, must be reliable. A common method to assure reliability is to compare these results with real-word data [2,13]: If there is no real-world data, assuring reliability of these references is challenging.

Evaluating and defining deviations of the simulation results from their references is another common method: To determine an acceptable model fidelity of a DES-model representing an existing manufacturing site, a deviation of ± 15 % is defined as the maximum tolerance from the real system's production throughput [2]. In this use case, the authors define the production throughput as the decisive key performance indicator (KPI) to which simulation results are compared to. Moreover, defining KPIs can also be refined [13]: To validate a simulation model, used to mirror people flows in a hospital, the authors define different specified indicators such as the minimum, maximum and average value of each KPI for certain activities with a maximum tolerated deviation of ± 5 %. However, in both publications it is not stated how the maximum tolerated value of deviation is defined.

The following three steps can be considered for model validation as well [14]: 1) face validity, 2) followed by testing the model with different input values and 3) comparing the model to a baseline model, that represents an existing system. Step 1 (face validity) and step 2 (variation of input values), however, do not assure the simulation results' accuracy due to missing comparisons with real-world data. Step 3 (comparison with a baseline model) also faces challenges: It prerequisites the baseline model`s results to be reliable and that conclusions are allowed to be drawn from the baseline model to the model in evaluation. Additionally, the author states that a model, representing a new system design, can be compared to assumptions and specifications.

3 Research Method

The research method proposed to validate a new simulation model of a system that does not exist yet is to design it from a base-structure of an already validated model. To be allowed to draw conclusions from the validated base model to the new model it must be ensured that both simulation models are designed with the same simulation components and process logics, using the same simulation parameters. A positively conducted validation process of the base model, by comparing its simulation results with the KPIs of an existing, physical system, allows to consider the new model as pre-validated and furthermore enables the implementation of an optimization process.

4 Use Case

During the development phase of a new intralogistics system referred to as 'System B', a high-fidelity DES-model is built to represent this new system. This new model is referred to as 'Model B'. Since the real system does not yet exist, real-world data cannot be considered for model validation. However, reliable simulation results are crucial before optimization measures are implemented [6]. To address this, the design of 'Model B' is based on the design of a validated simulation model, 'Model A'. Validation of this model is achieved by comparing the simulation results with the KPIs of its physical system and ensures that it accurately represents the real-world system. 'Model A' represents an existing, state-of-the-art intralogistics system referred to as 'System A'. Since 'Model B' is based on 'Model A', they share identical process controls, logical structures, simulation components and parameters. These similarities allow comparisons between the models and enabling conclusions to be drawn from one model to the other. Given that 'Model A' and 'Model B' share the beforementioned similarities, the validation of 'Model A' implies that 'Model B' can be considered pre-validated. This approach enables analysis of optimization measures in 'Model B' while ensuring the reliability of its simulation results until thorough validation can be conducted by comparing the model results with real data. Both simulation models are designed as high-fidelity models, resulting in detailed simulation outputs and enable to run experiments to analyse various KPIs.

The software used to build both simulation models is FlexSim 20.2.3. FlexSim allows to control simulation processes using process flows, defined by a series of individual process activities. Both simulation models use the same process flow structure, built by the same activities with the same process logics and parameters. To analyse the models suitable KPIs from various fields of applications are considered [8,15]. Simulation results of an optimization approach, in which the number of personnel is reduced, are compared with the results of its reference scenario with nonreduced number of personnel. The Kolmogorov-Smirnov (KS)-test is used to evaluate the results. A positive result from the KS-test allows acceptance of a formulated null hypothesis. Otherwise, the null hypothesis must be rejected.

Both intralogistics systems under consideration, represented by 'Model A' or 'Model B' include a conveyor system, and a security control area managed by personnel. In these systems, customers (PAX) hand over their items at interaction areas, after which the items are transported for quality control and later returned to the customers at the reclaim area. Customers must undergo a security check before retrieving their items. Once they have completed the security check and received their belongings, they exit the system. These types of intralogistics systems are typically used to conduct security checks on customers and their belongings before allowing them to enter restricted areas. The difference between the new system and the state-of-the-art system is the automated buffering system within the new system. Within the state-of-the-art system items are either manually buffered by personnel or they are buffered within the conveying system, which is supposed to transport items. Despite the differences in manual and automated buffering, the simulations' logic structures in both models are designed identically, using the same simulation parameters. This allows conclusions to be drawn from the base model to the new model.

5 Results and Discussion

Table 3: KPIs used for validation of 'Model A'.

KPI	Description	Value	Unit
α	average PAX throughput within peak hour	854	customers per hour
β	maximum PAX throughput	223	customers per 15 minutes
γ	average waiting time	≤ 3	minutes
δ	maximum tolerated waiting time	5	minutes

Validation of 'Model A' is performed by comparing its simulation results with the KPIs of the corresponding real-world system. Table 1 lists the KPIs, which are provided by an industrial partner.

Customer throughput in 'System A' is evaluated over a 24-hour period in 15-minutes intervals. The peak hour, representing the most critical period, is the focus of the validation process. If 'Model A' can mirror the real-world scenario within this peak hour, it is likely capable of representing any other system situation that is not critical. The average customer throughput within the peak hour is 854 customers per hour (KPI α) with its absolute maximum of 223 customers per 15 minutes (KPI β), equating to 892 customers per hour. Internal evaluations by the industrial partner show that customers experience an average waiting time of less than 3 minutes (KPI γ), and their maximum tolerated waiting time is 5 minutes (KPI δ). KPIs α and β set the lower boundaries for the system's performance, while KPIs γ and δ define the upper boundaries, which must not be exceeded. A successful validation requires the model to operate within these constraints.

For validation the simulation model is tested under two scenarios, in which customer arrival rates define the model load. The interarrival time automatically adapts to a constant value as a function of the number of arriving customers. The first validation scenario uses different but constant arrival rates over a test duration of 1 hour. The second scenario uses the evaluated customer throughput values within the peak hour as the effective load on the model.

5.1 Validation Scenario 1: Model under constant Load

In this scenario, customer throughput is evaluated as a function of the number of customers entering the simulation model. Different system loads are analysed by varying the constant rate of customers entering the model. The experiment starts with a sub-scenario and constant load of 750 customers per hour. The load is then increased in increments of 25 customers per hour in further sub-scenarios, reaching up to 975 customers per hour, which is approximately 110 % of KPI β, given the chosen step size. Since simulation input values are derived from statistical distributions, each sub-scenario is replicated 25 times to generate average values.

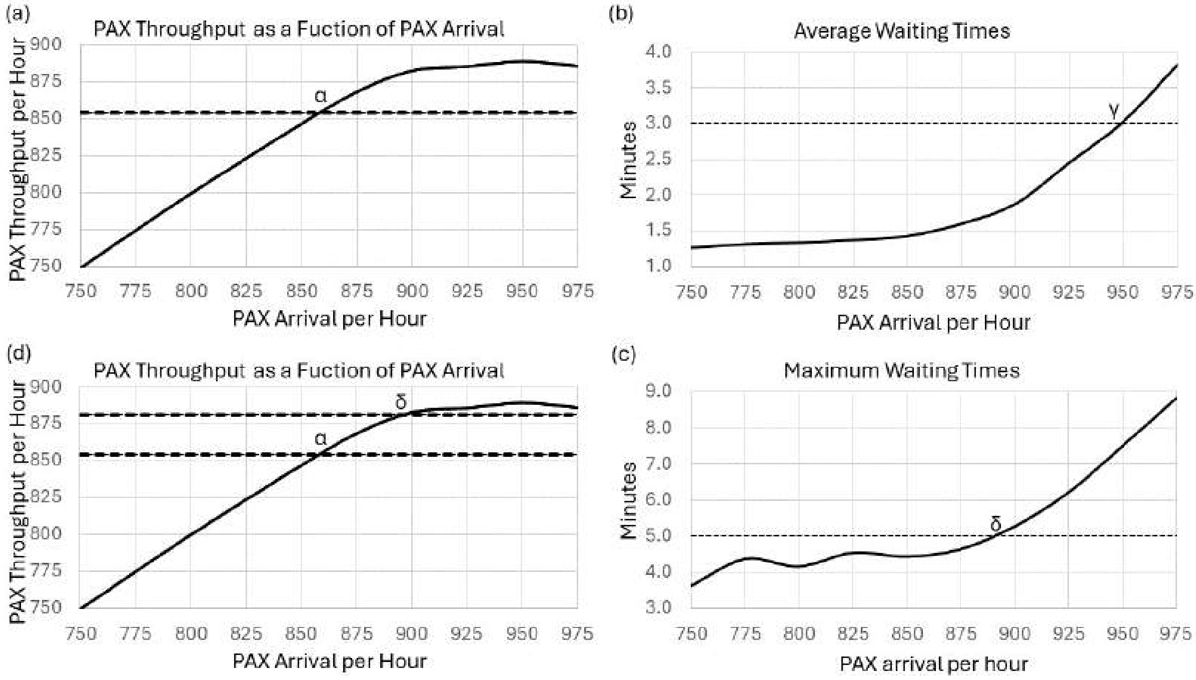

Figure 14: Evaluation of the KPIs of 'Model A'.

The analysis of the model's throughputs, as a function of arriving customers, leads to the following conclusion, see Figure 1: The lower boundary, defined by KPI α, is shown in the upper-left figure (a) of Figure 1. KPI β is not considered in this experiment due to the constant system load. The figures (b) and (c) on the right-hand side of Figure 1 show that the upper boundary, set by KPI δ, is more restrictive than that of KPI γ. These boundaries suggest that the model can handle up to 883 customers per hour without violating any given KPI, see (d) in Figure 1. Thus, the simulation model is validated for accurately representing the real-world system under constant load conditions, meeting all requirements for customers throughputs without breaching the boundary conditions set by the KPIs.

5.2 Validation Scenario 2: Model under effective Load

Table 4: Quarters considered for the validation of 'Model A' with values from the effective peak hour.

Quarter of an hour	Description	Value (Customers per 15 minutes)
I	start-up phase	186
II	peak hour	216
III		223
IV		214
V		201
VI	decay phase	193

The maximum constant load the model can handle is 883 customers per hour, slightly below 892 customers per hour, which is the equivalent of KPI β of 223 customers per 15 minutes. This means the model cannot process the peak load as a constant rate over 1 hour. Since the maximum load is not permanent over 1 hour, however, the model's performance is evaluated under the effective peak hour's load, in a second validation scenario. For this evaluation, the phases of start up and decay are considered, too, see Table 2. Because simulation input values are derived from statistical distributions, the validation scenario is replicated 25 times to generate average values.

Table 5: Customers' average and maximum waiting time.

Description	Value	Unit
average waiting time	1,5	minutes
maximum waiting time	4,5	minutes

The simulation results of this experiment show that the model meets KPI β by processing all customers without violating KPI γ (average waiting time) and KPI δ (maximum tolerated waiting time), see Table 3. Although the peak value of 223 customers per 15 minutes exceeds the model's equivalent constant load capacity from validation scenario 1, the system remains stable because this peak is temporary, only. Once the load decreases to 214 customers per 15 minutes in quarter IV, the model continues to handle the people flow within acceptable waiting times. Thus, the simulation model successfully represents the real-world system under effective peak hour conditions, too.

It can be concluded that 'Model A' is capable of mirroring its associated system in different scenarios, under different loads without violating any of the specified KPIs, allowing to accept 'Model A' as positively validated.

5.3 Optimization Analysis

With 'Model A' successfully validated, 'Model B' is considered pre-validated due to the shared process logics and simulation components of both models. The next step is to determine if 'System B' can operate with a reduced number of personnel while maintaining the same customer throughput. This is done by comparing the throughputs of two scenarios: the reference scenario with the full personnel level and the optimized scenario with reduced personnel. For each scenario, throughput values from 100 replications are subjected to a Kolmogorov-Smirnov (KS)-test. In this use case the KS-test is used to assess whether two data sets may originate from the same distribution. To accept this assumption, the KS-test's result must be greater than the chosen level of significance. In this case, The KS-test is preferred over the χ^2 test, since the KS-test's result reflect the absolute, maximum deviation rather than the relative deviations of 2 data sets [12]. Therefore, the KS-test is the more conservative test.

5.3.1 Distribution Analysis

The reference scenario's data set is analysed to identify the best-fitting distribution. The results show that the data follow a Gaussian distribution with a mean of 1573.16 customers per hour and a standard deviation of 93.35 customers per hour. The fitting test yields a mean square error of less than 0.2 %, indicating that the data can be appropriately parameterised as a Gaussian distribution with the above-mentioned parameters.

5.3.2 Kolmogorov- Smirnov-Test

The following hypothesis are formulated:

Null hypothesis: 'Model B' achieves the same maximum customer throughput in the personnel reduced configuration as it does in the nonreduced configuration.

Alternative hypothesis: The personnel reduced configuration results in lower customer throughput than the nonreduced configuration.

The KS-test is conducted in Python using the 'kstest'-function from the 'scipy.stats'-module, with a significance level of 0.05. The KS-test result of 0.47 exceeds the significance threshold. Therefore, the null hypothesis is accepted, confirming that the data set from the optimized configuration may originate from the non-personnel reduced configuration. Hence, 'Model B' in its personnel reduced configuration is likely to achieve the same customer throughput as in the configuration of full personnel level.

6 Summary and Outlook

To ensure reliable simulation results of a model representing a yet-to-be-built system, this paper proposes a method to pre-validate this new model by validating a second model that represents a state-of-the-art system. Both simulation models share the same process flow, simulation logics and components enabling conclusions to be drawn from the validated model to the model under evaluation. Validation is conducted by comparing various real-world key performance indicators (KPI)s with the simulation results under different scenarios.

An optimization measure for reducing personnel in the new system is analysed using the Kolmogorov-Smirnov (KS)-test. The test results indicate that the personnel reduced system is likely to achieve the same customer throughput as the full-staffed system, supporting the effectiveness of the proposed optimization. Even if the new simulation model is subjected to pre-validation, this does not replace a thorough validation using real-world data. It is recommended to conduct a validation process as soon as the real system is built, using its real data. Changes in the new model that affect the model's process logic and cause deviations from the reference's model logic, must not be applied. These changes may result in the models being incomparable, prohibiting to draw conclusions from one model the other.

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AUTHOR INDEX

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