AWK'23

May 11-12, 2023

Empower Green Production

Conference proceedings

WZL | RWTH AACHEN UNIVERSITY

Fraunhofer IPT

Foreword

Not only higher energy efficiency, CO_2 savings and less scrap characterize sustainable production. If we want to “Empower Green Production”, the paradigm shift is to extend the use cycle by transferring products or assets beyond their original life cycle into a multiple life cycle by adding a perceptible extension of functionality. Life-extending measures such as the timely replacement of existing components or assets with refurbished ones or those that can offer upgrades with completely new functions to end customers exemplify our understanding of a value-added circular economy. It differs from the generally intuitive understanding of "circular economy" in that not only are raw materials and energy recovered from used products, but used products and machines are specifically refurbished, industrially upgraded and used for a significantly longer period of time and potentially in a different context.

The digital shadow, along with specific technological and technical solutions, which were researched in the Aachen Cluster of Excellence "Internet of Production", creates the conditions for exploiting this – by far the greatest – sustainability potential of industrial production. In the future, new connectivity and data technologies will help companies save up to 50 percent of their industrially used resources and emissions, while at the same time enabling them to manufacture and offer complex series products up to 30 percent more cost-effectively than before. Household appliances, cars, machinery and plants can thus be systematically upgraded for a second, third or fourth life, without customers having to forego the added performance and appeal of new products created in parallel.

Ensuring the future viability of manufacturing companies against the backdrop of growing global challenges posed by climate change and the associated political and economic measures is the goal of the 31st AWK, the international Aachen Conference for Production Technology. The guiding theme of this year's AWK – "Empower Green Production" – represents the joint efforts of science and industry to achieve the urgently needed transformation towards green production.

In past editions of our conference series, we already used examples of successful research and industrial projects in the 2010s to show the opportunities offered by the comprehensive networking of machines and plants. Whereas AWK'21 dealt in detail with how the database obtained can serve as the basis for an "Internet of Sustainability," the next logical step for us is now to use these resources not only to increase productivity, as in the past, but above all for the transformation towards circular production. With this concept of a value-adding circular economy, for example, the (F-)ESG criteria could also be achieved many times better than with the classic, limited approach to the circular economy. The expansion of production boundaries beyond the factory gates and the inclusion of the information gained in the user cycle enables higher industrial value creation and at the same time increases the control options in the direction of increased resilience.

Using initial concrete examples from current industry and research projects, this year‘s AWK’23 would like to show which technologies and strategies will promote this transformation, how companies can select their individual tools for the change from the wealth of methods available, and with which challenges proximate production research can provide targeted support. The four central thematic blocks of the AWK include contributions on high-performance, storage-optimized and resilient data infrastructures, on technologies and processes for a properly functioning circular economy, on modelling and analyzes aimed at more resource-efficient manufacturing, and on scenarios and business models for sustainable value creation.

Under the guiding theme "Empower Green Production", we are taking up the complex challenge of the transformation to a value-adding circular economy, and have discussed our ideas and concepts with top-class teams of experts from industry and science at the 31st AWK. Together we want to set impulses and enable companies in the best tradition of the Aachen Machine Tool Colloquium to make their production equally more efficient and more sustainable.

AWK'23 is a renowned network meeting and hybrid information hub at the same time. Accompanied by the international top-class lecture program and with thematic tours of the host research facilities – on site in Aachen as well as digitally – the conference offers a comprehensive insight into the trends of applied research and development for specialists and executives from industry and science.

This conference proceedings, which takes up and reflects the contents of the event program, can serve as an incentive to initiate a conversation with us, with the expert teams and with the speakers, and to become an active protagonist of a value-enhancing circular economy yourself. We are pleased to make our research results available to a wide circle of interested parties and would like to thank all those who have contributed with great personal commitment to the discussion and the preparation of the presentations and the contributions in this book.

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Prof. Dr.-Ing. Christian Brecher

Prof. Dr.-Ing. Robert H. Schmitt

Prof. Dr.-Ing. Dipl. Wirt.-Ing. Günther Schuh

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Holder of the Chair of Manufacturing Technology,
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Greeting

Univ.-Prof. Dr.-Ing. Lutz Eckstein
President VDI

Production technology of the future - resilient, intelligent and sustainable

Current crises such as pandemics and wars, but also ongoing climate change, show us how necessary it is for companies and society to be able to adapt to changes in product availability and supply chains.

In the coming years there will be further disruptive changes. In Germany, we have to adapt to scarce and expensive energy, and to adapt our production systems in such a way that we work with the raw materials that we import as carefully as possible and in closed value-added cycles. Our goal must be a sustainable circular economy – as inde-pendent as possible from fossil fuels – which meets the global emissions- and climate-targets and is simultaneously resilient and adaptable.

In all sectors in Germany, it is important to implement processes that make production more sustainable. We have to decarbonize, recycle and reuse all materials, recycle waste immediately, and avoid waste over the entire production life cycle, as well as to generate, distribute and use energy intelligently. With the heading "Empower Green Production", it is clear that we are still in a global competition in which the best solution counts to make production truly green. The goal must be to think and act in a circular manner and to implement changes as quickly as possible.

According to the four “Rs” – Rethink, Reuse, Reduce, Recycle – it is important to consider the entire product life cycle. Since recycling usually only works as downcycling, reuse in combination with refurbishment should also play a major role in order to generate maxi-mum effects.

Specifically, it is important to consider two footprints of a means of production: the man-ufacture of the machine; and the use and disposal of the machine. So here, too, a con-sideration of the entire life cycle – from cradle to grave – is required!
I am convinced that, based on your excellent research and systematic development, you will succeed in creating a resilient, intelligent and sustainable production technology which will help ensure the future of our manufacturing industry as a pillar of Europe.

Greeting

Sibylle Keupen
Lord Mayor of Aachen

Multiple crises such as natural events and the war of aggression on Ukraine are challenging companies in a way never seen before. Nevertheless, it is important to think ahead together and shape our future. The current challenges are also an opportunity.

The transformation to a more sustainable, energy- and resource-efficient industry and economy must succeed. We have a responsibility to make climate protection socially and economically sustainable for future generations. To do this, we need to develop even more momentum.

The manufacturing industry is still highly dependent on global logistics chains, fossil energy, and rare raw materials. A circular economy that is less dependent on fossil fuels can help create greater resilience and security while helping to meet global emissions and climate targets.

How to overcome dependence on conventional energy suppliers is the topic of the 31st Aachen Machine Tool Colloquium (AWK). Internationally renowned experts from industry, politics and science will discuss new technologies and concepts for a more crisis-resistant and at the same time greener production in the future under the motto "Empower Green Production".

The colloquium is a unique flagship for our city of Aachen and highlights the interdisciplinarity and industrial relevance of this location. I wish all participants an interesting exchange about opportunities, experiences and ideas.

Greeting

Prof. Reimund Neugebauer
President of the Fraunhofer-Gesellschaft

Sustainable, innovative production technologies are essential for increasing productivity while maintaining climate targets, reducing dependence on fossil fuels, and, thus, securing Germany's long-term competitiveness as a technology location.

Digital transformation in particular provides numerous opportunities for sustainable and circular industrial production by networking people and machines in an intelligent system with real-time control. The successful implementation of a circular economy comprises three elements: first, resource-efficient products, processes, and production systems; second, circular product lifecycles, i.e., circulation of products and resource-efficient (re)manufacturing; and, finally, the circular materials lifecycle with renewable raw materials. All of these measures must be supplemented and flanked by digitalization, AI, and robotics.

Sustainable and circular production also plays an important role in gaining independence from volatile raw material markets and in saving costs by improving material use. Against this background, the "Empower Green Production" focus of the Aachen Machine Tool Colloquium 2023 perfectly addresses the current times. Both a fundamental openness to technology and close cooperation between industry, science, and politics are essential for a successful transformation and for securing our international competitiveness. Let us set the course for a successful future together.

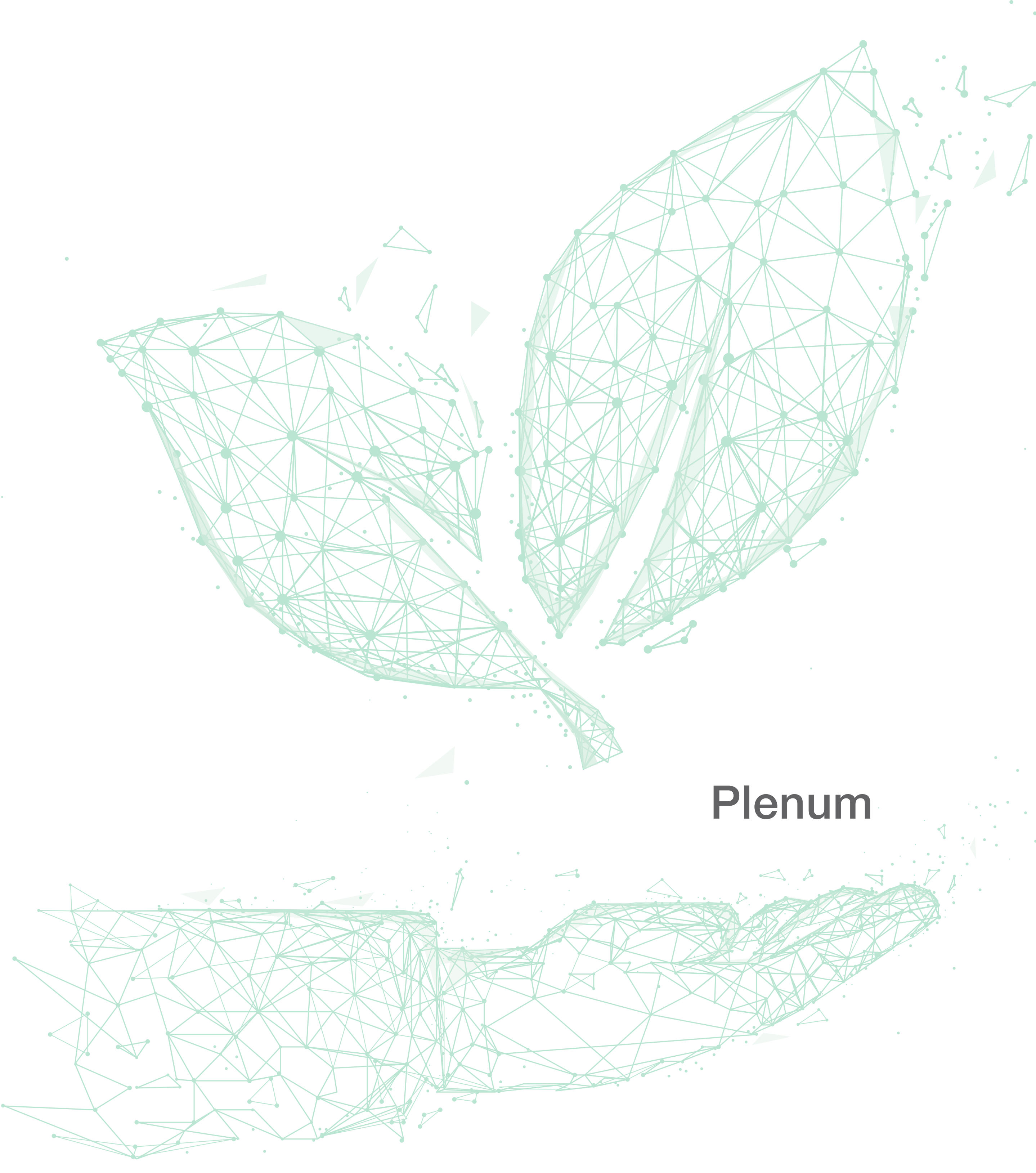

Digital labs
Take a tour!

Top-level research up close – experience the virtual 3D campus

At the campus Digital Twins are not only used in research. In the 3D environment of the machine halls and laboratories of the WZL | RWTH Aachen University and Fraunhofer IPT, the nine thematic tours can be visited and experienced virtually. In this way, targeted information on the rich diversity of research and development topics of the two host institutes can be provided to complement the AWK. All with the focus on sustainable production.

Digital lab tours:

1. Data-driven sustainable manufacturing
2. Sustainable manufacturing through data-driven optimization of process chains
3. Sense - think - act: closed-loop data for closed-loop lifecycles
4. Production analytics in machine tools
5. Innovative gear analysis for a green production
6. Smart automation lab
7. Next generation propulsion systems
8. Digitization as an enabler for green production
9. Enablers for sustainable production systems


Plenum

Plenary talk

Manufacture #LikeABosch – Producing Technology Invented for Life

Dr. Stefan Hartung
Chairman of the Board of Management, Robert Bosch GmbH

Year of birth:
1966

Current position:

since 2022	Chairman of the Board of Management, Robert Bosch GmbH

Previous positions:

2019-2021	Chairman of the Mobility Solutions business sector, Robert Bosch GmbH
2013-2019	Member of the board of management, Robert Bosch GmbH
2009-2013	President, Power Tools division

Studies:

1993	PhD at RWTH Aachen University
until 1990	Studies of Mechanical engineering, specializing in production engineering at RWTH Aachen University

Manufacture #LikeABosch – Producing Technology Invented for Life

Dr. Stefan Hartung
Chairman of the Board of Management, Robert Bosch GmbH

Advanced and high-volume production is at the heart of our economies turning ideas and digital designs into tangible goods for the masses.

For us, this ranges from the creation of tiny structures in specialized semiconductors, to fabricating power tools for millions of users and automotive products for millions of drivers, as well as to the provision of manufacturing technology and services themselves.

With the implementation of advanced green technologies, sustainable, circular approaches, and resilience measures, modern production facilities offer great opportunities to achieve these goals for supply chains and economies at large.

Thus, for us, high-quality manufacturing is a cornerstone in achieving the goal of our technology, which is invented for life, too.

Plenary talk

Circular Economy as an industry strategy for sustainable value creation made in Europe

Prof. Dr.-Ing. Dr.-Ing. E. h., Siegfried Russwurm
President, Federation of German Industries (BDI e.V.)

Year of birth:
1963

Current positions:

since 2021	*President, Federation of German Industries (BDI e.V.)*
since 2019	Chairman of the Supervisory Board, thyssenkrupp AG
since 2019	Chairman of the Shareholders' Committee and the Supervisory Board, Voith GmbH & Co. KGaA

Previous positions:

2008-2017	Member of the Managing Board & Chief Technology Officer, Siemens AG
1992-2007	various management positions, Siemens AG

Studies:

1983-1988	Production Technologies
1988-1991	Computational Mechanics (PhD)

Circular Economy as an industry strategy for sustainable value creation made in Europe

Prof. Dr.-Ing. Dr.-Ing. E. h., Siegfried Russwurm
President, Federation of German Industries (BDI e.V.)

We need a circular economy to achieve our climate goals and secure our raw material supply. According to the Circularity Gap Report, only 7.2 percent of the global economy is currently circular. However, companies can design products in such a way that as few – and, above all, sustainable – materials are used. Sustainable business models need to focus on longevity, repairability, and recyclability. Not considering a product's recovery potential means not understanding its full value potential.

Plenary talk

Autonomous Manufacturing for a Sustainable Future

Paolo Guglielmini
President and CEO, Hexagon

Paolo Guglielmini is President and CEO of Hexagon, a leading global provider of digital reality solutions. Guglielmini assumed this role in 2023 after serving as COO. Prior to that he led the strategic and commercial development of Hexagon's Smart Factory Solutions as President of Hexagon's Manufacturing Intelligence division. He has served in many key roles since joining Hexagon in 2010 – from strategy and business development to mergers and acquisitions and general management. Prior to joining Hexagon, Guglielmini held positions at CERN, European Council for Nuclear Research (in Switzerland) and Accenture (in Italy). He holds a Master of Science in engineering and a Master of Business Administration.

Year of birth:
1977

Current position:

since 2023	President and CEO, Hexagon

Previous positions:

2022-2023	Chief Operating Officer, Hexagon
2020-2022	Manufacturing Intelligence Division President, Hexagon
2017-2020	President and CEO, MSC Software (part of Hexagon)
2010-2017	Business Development, Manufacturing Intelligence Division, Hexagon
2004-2008	Project Lead, Engineering Department, CERN
2003-2008	Business Analyst, Accenture

Studies:

2009	Master of Business Administration
2002	Master of Science in Engineering

Autonomous Manufacturing for a Sustainable Future

Paolo Guglielmini
President and CEO, Hexagon

Our world is composed of finite resources. To conserve the environment, it is vital to reshape product lifecycles and create a value-added circular economy. When products reach end of life, we can do much more than recover the materials – we can refurbish and upgrade them to extend the product lifecycle and maximise the energy used to manufacture goods in the first place. But how can we ensure products are designed with end-of-life in mind, made to last, fit for reuse and ready for upgrade? This presentation will explore the complex equation of people, technology and process in the pursuit of greener production.

Driving optimization and innovation

Addressing key sustainability challenges such as decarbonization, waste reduction and resource protection requires a focus on productivity, quality and efficiency at every stage of the product lifecycle. To make manufacturing as planet friendly as possible we need to ask questions about everything – from the products we create, to the way they are designed, the way they look, the materials we use, the way they are created, and the way they are used and serviced.

Optimizing product design and production processes can help reduce waste, energy usage and emissions. But optimization alone cannot stop climate change – we must also accelerate innovation. Manufacturers need to innovate and bring sustainable product innovations to market – for example by making better performing products, using the best available materials in the most efficient ways, and developing more sustainable production processes.

Empowering people with technology

Leveraging data to its full potential, digital reality solutions empower makers with insight to make better products in better ways. They bring together innovation and optimization so sustainability concerns can be addressed more holistically. Deployed effectively, this technology can be enhanced with advanced automation and autonomous technologies to unlock the power of human ingenuity, enabling cross-functional teams to collaborate, solve problems, iterate faster and address complex but urgent sustainability challenges sooner.

This is the time for new ideas and bigger ambition. To achieve scalable sustainability, manufacturers must empower people with the data they need to make informed decisions throughout the product lifecycle.

Digitalizing the product lifecycle

Taking a data-driven approach throughout the product lifecycle offers a blueprint for greener production. Using digital tools to break down siloes and drive collaboration enables product developers to take a more holistic view of sustainability issues from design concept to delivery and make better decisions that will in time lead to a more sustainable manufacturing ecosystem.

In design – With an estimated 80% of a product's environmental impacts locked in at the design stage, it's important that development teams have as much information as possible to inform decisions about materials, processes and the product's purpose and required performance. Understanding the usage cycle and consumer behavior provides valuable insight, as does data from the production and quality assurance processes of previous iterations. The ability to understand the consequences of decisions in digital reality and test ideas can reduce prototyping, and ensure manufacturability and quality. Effectively leveraging data in the design process also opens the door to design for sustainability and eco-design approaches, supporting predictive maintenance, value-added upgrades, simple dismantling, re-manufacturing and recycling.

In production – Digital reality solutions enable process simulation and validation and optimise production to save resources and cut waste by reducing rework and scrap. Bringing the process of manufacturing closer to the design phase through continuous digital feedback helps to create optimized products in optimized ways that maintain design intent. Increasingly closed-loop automation helps to remove the potential of human error in processes and mitigate common issues such as tool wear, moving production closer to first time right.

In quality control and service life – Metrology solutions capture real-world data typically used for quality assurance, however its potential is much greater. Feeding measured data back into design simulations can improve a designer's understanding of the impact of the manufacturing process, or of the behavior of the part during service – helping give usage cycle insights that raise the bar for future developments.

Digitalizing products throughout the lifecycle also offers the potential to introduce digital product passports. With digital information embedded in products, manufacturers will gain transparency to improve the lifecycle sustainability of products by gathering and sharing information on how they can be repaired, broken down or recycled.

Harnessing the power of data

Data is the key to scalable sustainability, but it will only supercharge the march to greener product production when it is fully accessible to the right people at the right time. Siloed tools and rigid systems are hampering innovation. To change this, manufacturers need to connect data from different applications to form workflows and solve problems. Connecting this data centrally via cloud technology can provide advanced insight and power intelligent automation, while applying AI and machine learning techniques to autonomously make vast quantities of data usable and actionable to human experts. Only then can cross-functional teams fully leverage data, interact and share like never before, bring their ideas to life faster, and produce better products in new innovative ways.


HEXAGON
AREA 12

Make the difference

Let's rethink making. Let's shape a better future.

Securing the future for people and planet requires more than a rethink – we need to reinvent making.

This isn't about improving what exists, it's about rethinking everything we know about products and production. Hexagon technology empowers makers with the tools to create optimised products in new innovative ways – from concept design and material selection to simulation and production.

Dream the impossible and redefine what's real. Let's create the change we need to see. Together.

Empowering green production

Let's shape tomorrow, today

Makers shape our world. Define the way we live. Constantly strive for improvement. With a climate emergency staring humanity in the face – makers can make the difference.

Hexagon exists to empower makers to shape a better future – collaborating with designers, inventors, engineers, researchers and manufacturers, and providing the tools to unlock innovation and solve challenges.

Through efficient design, material selection, process, production and end-of-life planning, we can conserve energy, resources, money and time – taking manufacturing from problem to solution.

The innovation imperative

An opportunity exists, not simply to slow climate change, but to turn the tide. It is time for new ideas and bigger ambition.

Makers that place their focus on optimising what exists will lose out to innovators who rethink every aspect of products and production – disrupting the status quo with solutions that realign people with planet.

It's time to swap resources, energy and consumption for data, technology and innovation. It's time to give wings to your ideas.

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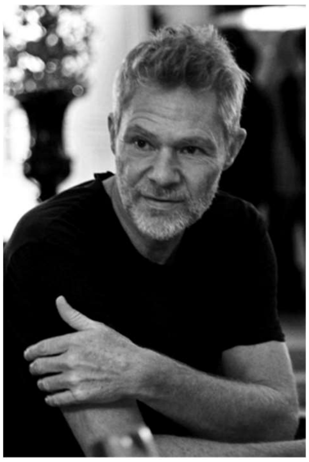


Plenary talk

Beyond Sustainability – Manufacturing a new mindset

Stefan Liske
Managing Director, PCH Innovations

Year of birth:
1966

Current position:

since 2021 Blank.AI Founder + Partner
since 2006 PCH Innovations Founder + Partner

Previous positions:

2003-2006 VW Group, Director Global Product Strategy + Innovation Projects
2000-2003 Arthur D. Little, Partner
1988-2000 BMW Group, Manager Special Vehicle + Design Division

Studies:

until 1993 Dipl.-Ing. Industrial Design, TU Munich
until 1993 Dipl.-Ing. Mechanical Engineering, TU Munich
until 1990 MBA, Thunderbird School of Global Management

Beyond sustainability – Manufacturing a new mindset

Stefan Liske
Managing Director, PCH Innovations

Sustainable transformation of production means requires a shift in both culture and technology, at every level of the organization. It is not just about machines and processes; it is about people. Without a shift in culture and consciousness, we will only make marginal improvements, while disconnection between and within us increases. To address this, we propose an innovation framework that promotes harmony between humans and machines. This framework consists of three parts: **Mindset, Organization, and Technology**.

Innovation **Mindset** explores practices that address our minds and hearts, creating deeper awareness of caring, interconnected, and ultimately healing states. Keeping the balance between Original and Artificial Intelligence.

Organization connects the shift in mindset to emerging production ecosystems that prioritize flow in networks over transactions in markets. It also highlights the need to embrace local, near, and far manufacturing capacity, open and adaptable fabrication systems, educational platforms, and spaces to build production communities. It even proposes a redesign of factories as Manufacturing Biomes.

Finally, the last pillar of the framework focuses on **Technology** applications that support this new human-machine harmony. It covers four main automation areas: design-to-make software pipelines, additive manufacturing, circular robotics, and generative AI.

The keynote by PCH Innovations will provide a wealth of insights, ideas, and cases, drawn from our work as a creative engineering studio for exploratory technology in Berlin.

Plenary talk

Transformation of the steel industry – how to save 2.5% of German CO2 emissions

Dr. Marie Jaroni,
Head of Decarbonization, thyssenkrupp Steel Europe AG

Year of birth:
1984

Current position:
since 2021 Head of Decarbonization of thyssenkrupp Steel Europe AG
since 2021 Member of the Supervisory Board of Eisen- und Hüttenwerke AG

Previous positions:
2017-2021 thyssenkrupp Steel Europe AG
2011-2017 McKinsey & Company

Studies:
2016 Promotion an der RWTH Aachen
until 2011 Studied metallurgy and materials engineering at RWTH Aachen University

Transformation of the steel industry –how to save 2.5% of German CO2 emissions

Dr. Marie Jaroni,
Head of Decarbonization, thyssenkrupp Steel Europe AG

tkH2Steel®: With hydrogen toward carbon-neutral steel

Steel production at thyssenkrupp is planned to be carbon-neutral by 2045. With our climate strategy, we are stepping up our previous activities to reduce emissions, accepting our social responsibility and showing our commitment to the 2015 Paris Climate Agreement. As an initial target for 2030, thyssenkrupp Steel is aiming to reduce emissions from its own production and processes and from the purchase of energy by more than 30 percent versus the base year 2018.

thyssenkrupp Steel is pursuing a technology-open approach and focusing on two parallel routes: The decisive step is the avoidance of CO2 through the use of hydrogen ("Carbon Direct Avoidance", CDA). This is complemented by the use of CO2 produced in steelmaking ("Carbon Capture and Usage", CCU).

thyssenkrupp Steel is continuously developing both ways. The company is always looking for even more efficient solutions or ways to accelerate the transformation, for example through new technological findings. In the hydrogen path thyssenkrupp Steel also always keeps an eye on the availability of hydrogen, as the hydrogen economy is still in its infancy. To force the rapid development of a supply infrastructure for green hydrogen, thyssenkrup Steel is a partner in various national and international projects and collaborations.

The first technology path contains the successive farewell to the blast furnace

In contrast to the blast furnace, DR plants do not produce hot metal, but solid sponge iron ("Direct Reduced Iron", DRI). By 2026, we will have built the first plant with a capacity of 2.5 million metric tons. This alone will save 3.5 million metric tons of CO2, about 20 percent of our overall emissions. By 2030, we aim to produce 5 million metric tons of CO2-reduced steel, and to cut CO2 emissions by more than 30 percent. Steel production at thyssenkrupp Steel is planned to be completely carbon-neutral by 2045.

It must be melted down into a hot metal-like product so that it can be further processed into high-quality steel. Together with equipment builders, thyssenkrupp Steel has therefore developed a completely new unit in order to optimize the hot metal system. It is an electrical power-operated melter, which is combined with the DR plant. Direct reduction plants with a melter – just like a blast furnace – continuously produce a liquid product comparable to conventionally produced hot metal.

As a result, the new plants can be seamlessly integrated into the existing metallurgical plant. The great advantage is that the existing and proven processes in the Duisburg-based BOF meltshops can be maintained. The liquid product is processed into the proven steel grades there. Thus, the Duisburg steelworks is continuing to boil steel like in the past – but with hydrogen and green power instead of coal.

The second technological method thyssenkrupp Steel is pursuing in its goal to become carbon-neutral by 2045 is the Carbon2Chem® project.

As part of a project funded by the German government, thyssenkrupp Steel has been treating process gases from steel production and processing them into basic products for the chemical industry since 2018. In this way synthesis gas, which until now has been obtained from fossil resources such as oil or natural gas, can be saved. On a test site close to the iron and steel plant, the company recycles process gases generated during steel production and processes them further. With the new process, thyssenkrupp Steel has produced ammonia and methanol from steel mill gases – the first time this has happened anywhere in the world. The basic chemicals are further processed in the chemical value chain into fertilizers, plastics or fuels, for example.

Using both of these methods – Carbon2Chem® and injecting hydrogen as a reducing agent – in parallel will allow thyssenkrupp to considerably reduce the emissions of its existing blast furnace route in future.

Plenary talk

5G – Manufacturing a sustainable future by breaking the energy curve

Joe Wilke
VP, Head of Center of Excellence 5G Industry 4.0, Ericsson

Year of birth:
1967

Current position:

since 2019	VP, Head of Center of Excellence 5G Industry 4.0, Ericsson Deutschland

Previous positions:

2016-2018	Program Manager „5G beyond Mobile Broadband“, Ericsson Schweden
2012-2016	Program Manager „Software Defined Networking“, Ericsson Deutschland
2010-2011	VP, Technology, Ericsson Silicon Valley (USA)
1994-2010	Technology Transformation Programs, Ericsson Deutschland
1994-1994	Operations Engineer, e-plus Mobilfunk

Studies:

until 2011	Degree (Dipl.-Wirt.-Ing.) in Industrial Engineering, Fernuni Hagen
until 1994	Degree (Dipl.-Ing.) in Electrical Engineering, RWTH Aachen

5G – Manufacturing a sustainable future by breaking the energy curve

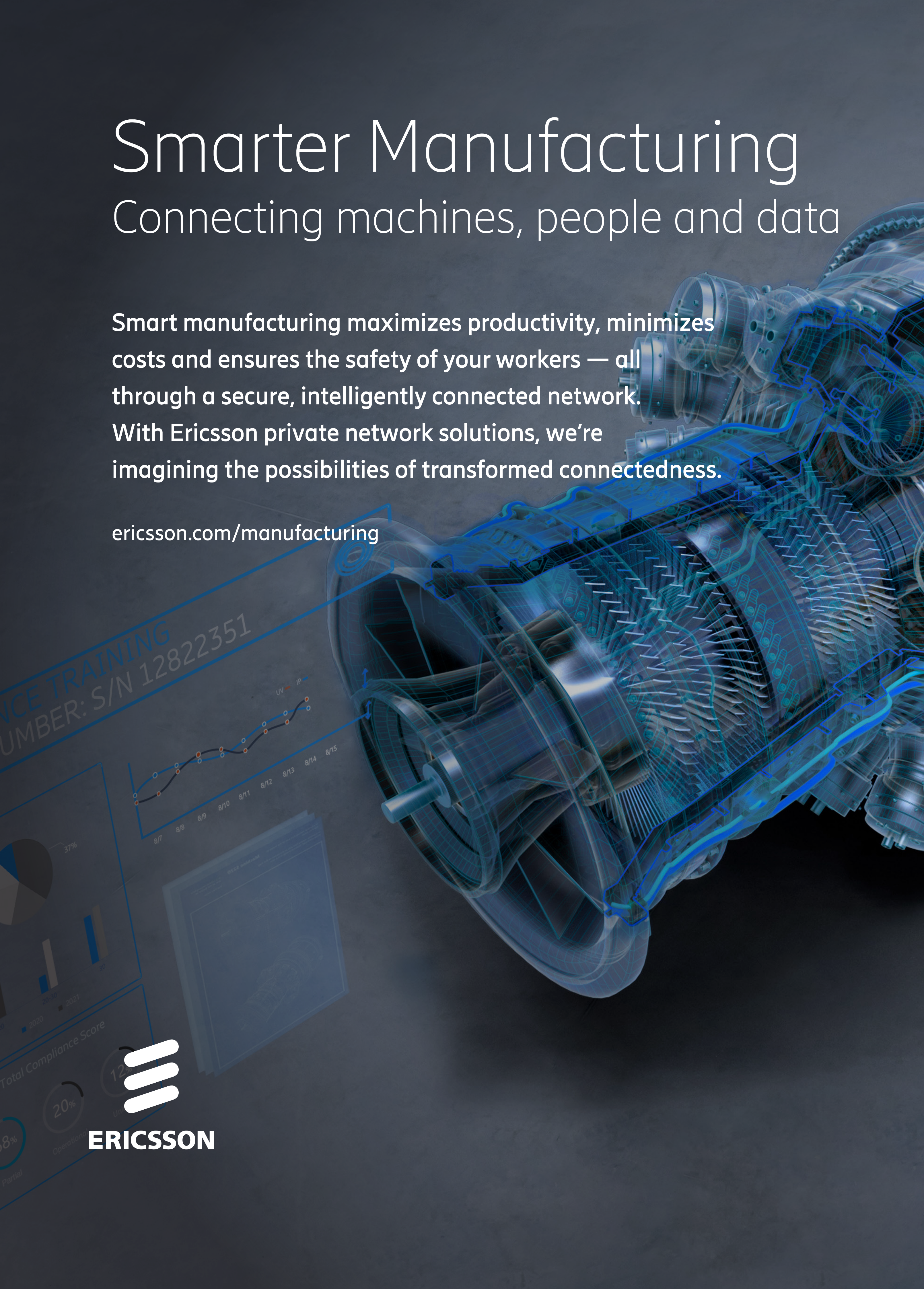
Joe Wilke
VP, Head of Center of Excellence 5G Industry 4.0, Ericsson

Every sector of society must work together to reach the global climate and energy challenge. Net Zero is the North Star of climate action and will be key for the industry. In the telecommunications industry, for instance, the deployment of new network generations usually means higher energy consumption. If 5G was deployed similarly as 3G and 4G, energy consumption would increase a lot. Thus, breaking the energy curve of mobile networks is of utmost importance and will have the benefit of reducing energy use, cost and environmental impact. Based on extensive research and development, this can be achieved through 1) operating site infrastructure intelligently with artificial intelligence, 2) building 5G with precision and 3) implementing energy-saving software in radio equipment. Furthermore, the lifecycle of network hardware shall follow a circular approach, where components are designed from sustainable material and facilitate re- use and recycling.

Sustainable, climate-friendly production also is the aim for most other industries, with a target to reduce carbon footprints and environmental impact. Next to the importance of contributing to sustainable development goals, industries can also yield economic profits from investing into green solutions. For manufacturers, this can be achieved through monitoring of the production via sensors and derivation of optimization potential in processes which can lead to lower energy consumption and to reduction of scrap and rework. Continuous monitoring provides real-time visibility of the status of critical, high- value assets and processes and enables prompt reaction to potentially hazardous situations. It also allows machine maintenance to be performed proactively instead of reactively. Robotics operations are optimized by live mapping their locations and routes, thus avoiding collisions and unnecessary slow-downs which prolong battery life.

This type of real-time monitoring requires a connectivity infrastructure that guarantees both flexibility and continuity in production, but also reliable transfer of large amounts of data – key characteristics of 5G. 5G is a platform that enables building up cyber-physical systems with a closed feedback loop – beginning with the collection of live production data through different types of sensors in the physical production area which are then analyzed in the virtual data layer. This is supported by artificial intelligence and ultimately leads to the automatic derivation of actions for the assets in the physical layer.

In this session, we will explore how 5G enables automated and connected factories to reduce their environmental impact while also benefitting economically from reduced resource usage.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Connecting machines, people and data
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Plenary talk

Transforming Industry Through the Industrial Metaverse: a Catalyst for Sustainability

Dr. Annika Hauptvogel
Head of Technology and Innovation Management, Siemens AG

Annika Hauptvogel has been Head of Technology and Innovation Management at Siemens since June 2021. In this function she is responsible for the strategy of Siemens Technology. She reports directly to the CTO of Siemens AG.

Annika Hauptvogel began her career at Siemens Mobility GmbH in 2015. In her former position she was responsible for the development of digital services for rail systems.

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Transforming Industry Through the Industrial Metaverse: a Catalyst for Sustainability

Dr. Annika Hauptvogel
Head of Technology and Innovation Management, Siemens AG

The world faces growing environmental challenges, generated among other things by CO2 emissions. Industry is responsible für 20% of global CO2 emissions and more than 30% of global energy consumption. Therefore, the industry today is faced with the challenge of reducing both. The Industrial Metaverse will play a major role to tackle these.

The Industrial Metaverse is the concept of a virtual world to mirror and simulate real machines and factories. It will be a world which is always on, allow for the interaction of an infinite number of people and assets, and offer the full immersion into a physics-based, photo-realistic and real-time simulation. In this digital environment people can break the barriers of distance and work together across countries and continents, enabling a whole new level of collaboration. Problems can be found, analyzed, and fixed quickly – or even discovered before they arise. And businesses and economies will be able to become more sustainable, driving the decarbonization and dematerialization of product design, their processes and production.

The Industrial Metaverse is still a vision, but it will be realized by technologies that exist even today. Digital twins are key building blocks for the Industrial Metaverse. The combination of several technologies like Artificial Intelligence, 5G/6G, Blockchain, Edge and Cloud Computing as well as Augmented and Virtual Reality will combine the real and the digital worlds even more.

The Industrial Metaverse will enable a sustainable industry by saving energy, improving efficiency, and reducing waste across all phases of the product lifecycle, which will be shown by different use cases from design & engineering and production to operation & service. All these use cases are interconnected with each other exchanging continuously data between physical and digital worlds.

During the design phase the Industrial Metaverse will allow more collaboration between stakeholders, also involving non-technical stakeholders in the process. That drives the democratization of simulations, allowing experts to communicate more effectively with non-experts. Therefore, it will be possible to explore designs and manufacturing options more interactively, involving more viewpoints, to create better resilient products. The whole process will be more efficient and by trying out different scenarios in a virtual environment before building them in real, material is saved, and waste is reduced.

A major use case in the production phase will be the virtual commissioning of factories: virtually installing and testing new devices and software without disturbing the ongoing production line. The industrial metaverse will allow to visualize the new equipment in the factory in augmented reality (AR) technologies and simulate interaction with existing manufacturing assets. Industry professionals will collaborate in real-time, troubleshoot issues before they occur in the physical world, and develop new, innovative solutions, which can prevent dangerous situations and enhance worker safety. It will forever change the way we collaborate – within organizations, ecosystems and between firms and their clients and customers and become a key enabler of Industry 4.0. It will enable to test more in the virtual world with less resources from the real world. So resilient factories can be modeled and optimized in a virtual environment, reducing the need for physical testing and experimentation. These factories will rely on artificial intelligence and machine learning algorithms to optimize production processes, reduce downtime, and minimize waste.

For operations the Industrial Metaverse allows not only the virtual training of the workforce on unusual scenarios, including the access to virtual experts at large scale but also it helps to visualize data and augment information (e.g., virtual sensors) associated with the physical asset though AR technology using either glasses or a tablet.

The Industrial Metaverse will disrupt industries and enable sustainability. By leveraging this technology, we can create more sustainable and efficient industrial systems, reduce waste, and promote circular economy principles. Overall, it is a catalyst for building a more resilient, circular, and sustainable future.

Digital industries are sustainable industries…

Our resources are finite, but data is not. Digitalization and automation are the game changers for mastering the challenges of today and tomorrow – so no time to waste: Become a digital enterprise with the help of our digital business platform Siemens Xcelerator. Our digital enterprise portfolio increases flexibility, transparency, and resource efficiency along the value chain with innovative motion control and factory automation solution.

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... sustainable industries that grow forward

Make your sustainability goals actionable while driving growth and profitability! While we help our customers achieve their sustainability goals, we are also committed to lowering the carbon footprint in our own operations to net zero by 2030.

Plenary talk

Investing in the Technology Champions of Tomorrow

Dr. Elisabeth Schrey
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Investing in the Technology Champions of Tomorrow

Dr. Elisabeth Schrey
Managing Director of DeepTech & Climate Fonds

Many young entrepreneurs dedicate themselves to the challenges of our society and economy. In particular, companies with disruptive technologies or new resource-saving business models have longer commercialization cycles and greater capital requirements.

Investments in such companies enable a rapid transformation into a resource-saving and climate-neutral economy. This transformation is fraught with uncertainty and risk, but it is also the greatest opportunity for our economy.

With growth capital and long-term commitment, we want to contribute to developing independent and successful technology champions in Germany and Europe.

Session 1
Data structures for resilience

1.1 Data Structures for Resilience in Life Cycle Sustainability

R. H. Schmitt, M. Bodenbenner, H. Brings, B. Montavon

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Abstract

Data Structures for Resilience in Life Cycle Sustainability

The perspective of tomorrow's life cycle sustainability combines the megatrends of sustainability, digitalisation and resilience under the boundary conditions of responsible use of resources. The cross-life cycle consideration of defined sustainability criteria for a product and its components with the aim of maintaining or increasing value focuses these three megatrends on the necessary data management. The data determine the technological scope and enable an objective evaluation. The effective use of already existing building blocks such as smart sensors, digital twins, cyber physical systems, intelligent algorithms for pattern recognition and decision making and others need to be complemented by the necessary advanced communication in terms of speed, latency and jitter. The temporal horizon of life cycle sustainability and the a priori unknown use of data lead to further challenges: Beyond production and user cycles, data must be reliably findable, accessible, interoperable and reusable for a long period of time and for many stakeholders, even if there are several decades, numerous data owners and multiple system breaks between data collection and data use. The FAIR and FACT principles offer a suitable framework, provided they are tailored to the domain of production technology, to enable economically successful circular value creation. The article presents an approach for this and illustrates it with various examples from the areas of 5G, sensor data management, automation and quality management.

Keywords: Data Management, Resilience, Sensing, Sustainability

Kurzfassung

Datenstrukturen für eine resiliente Life Cycle Sustainability

Die Perspektive der Life Cycle Sustainability von morgen vereinigt die Megatrends Nachhaltigkeit, Digitalisierung und Resilienz unter den Rahmenbedingungen eines verantwortungsvollen Umgangs mit Ressourcen. Die Betrachtung definierter Nachhaltigkeitskriterien für ein Produkt und seine Komponenten über mehrere Lebenszyklen mit dem Ziel des Werterhalts oder der Wertsteigerung, fokussiert diese drei Megatrends auf das notwendige Datenmanagement. Die Daten bestimmen den technologischen Gestaltungsspielraum und ermöglichen eine objektive Bewertung. Die effektive Nutzung bereits existierender Bausteine wie Smart Sensors, Digital Twins, Cyber Physical Systems, intelligente Algorithmen zur Mustererkennung und Entscheidungsfindung und andere sind durch die notwendige fortschrittliche Kommunikation in Bezug auf Geschwindigkeit, Latenz und Jitter zu ergänzen. Der Zeithorizont der Life Cycle Sustainability sowie die a priori gegebenenfalls unbekannte Nutzung der Daten führen zu weiteren Herausforderungen: Diese müssen über Produktions- und Nutzerzyklen hinaus für einen langen Zeitraum und für viele Stakeholder zuverlässig auffindbar, zugänglich, interoperabel und wiederverwendbar sein, selbst wenn zwischen der Datenerhebung und der Datennutzung mehrere Jahrzehnte, vielzählige Dateneigner sowie mehrfache Systembrüche liegen. Die FAIR- und FACT- Prinzipien bieten einen geeigneten Rahmen, sofern Sie auf die Domäne der Produktionstechnik zugeschnitten werden, um wirtschaftlich erfolgreiche zirkuläre Wertschöpfung zu ermöglichen. Hierfür wird im Beitrag ein Ansatz vorgestellt und anhand verschiedener Beispiele aus den Bereichen 5G, Sensordatenmanagement, Automatisierung, und Qualitätsmanagement illustriert.

Schlagwörter: Datenmanagement, Resilienz, Sensing, Nachhaltigkeit

1 Motivation

The promise of increasing prosperity for everyone and a rising overall population in relation to the preservation of nature and the environment so that responsibility for future generations can be met is one of the greatest social, political and economic challenges of the 21st century. This is also reflected in the political macro targets for reducing climate change - for example, achieving CO_2 neutrality by 2050 or the so-called 1.5-degree target. The natural catastrophes of the recent past, the current energy crisis and the increasing political awareness are thus also placing the topic of sustainability in the operational and strategic focus for manufacturing companies.

The megatrend, digitalization, with the associated metaphors of cyber-physical systems realized as Digital Twins is seen as an enabler for the sustainable design of production technology. This is being acknowledged both in the production technology community [1], the research of new technologies [2] as well as concretized in the orientation of the European politics. [3]. Nevertheless, the implementation of Industry 4.0 has so far focused primarily on the connectivity of resources [4]. This is accompanied by two challenges: in order to exploit the potential of data in terms of sustainability, the specific Digital Shadow must not only be stored, but also aggregated and processed into information, knowledge as well as specific actions [2]. Second, data cannot be collected in virtually unlimited amount over a long period of time without becoming a significant driver of the CO_2 footprint itself. The energy consumption of data storage depends on many factors in each individual case, but a rough calculation estimates a CO_2 equivalent of about one ton for cloud storage of 100 gigabytes over 10 years. At the same time, the expectation that the relevant amount of data will increase to about 80 trillion gigabytes by 2025 [1], was already exceeded in 2022 with almost 100 zettabytes generated, stored, distributed and consumed. In this estimate, full storage of the entire created annual gross data volume over 10 years would be associated with about 1000 billion tons of CO_2 equivalent – more than 20 times the global CO_2 emissions in 2021 [5]. Although many technology companies - including hyperscalers - are themselves working to make their data infrastructure more sustainable [6], it is clear that this aspect alone requires consistent data management as well as strategies for efficient aggregation of data and subsequent reduction of raw data.

A third, current megatrend is resilience as a desirable characteristic for society and thus also for its manufacturing companies. In globally connected, complex production systems, unexpected disturbances quickly have a far-reaching impact [7] - for example, when container prices increased eightfold in the logistics sector due to a crisis situations, calling into question the profitability of globally distributed production [8]. If we consider not only profitability, but assume multidimensional business goals along the FESG criteria [9], a direct link between resilience and sustainability emerges.

The three megatrends of sustainability, digitalization and resilience are focused the perspective of Life Cycle Sustainability, as this enables both macro targets and technological strategies to be specified. It also creates a frame of reference for implementing the necessary data management. The central aspect of this is suitable data structures. This paper considers the above focus on megatrends in three main sections: First, the concept of Life Cycle Sustainability is motivated and the role of data along the knowledge pyramid is highlighted (Section 2). Then, the concept of resilience for Life Cycle Sustainability is interpreted and implications for data structures and algorithms are derived (Section 3).

Finally, technological solution approaches are presented as building blocks for achieving resilient Life Cycle Sustainability (Section 4).

2 Data as enabler of Life Cycle Sustainability

2.1 Life Cycle Sustainability - Definition and objectives

The origins of Life Cycle Sustainability lie in Life Cycle Thinking [10]. Life cycle thinking calls for consideration of the cumulative footprint of a product over its entire life cycle, often referred to as *cradle to grave.* Life cycle thinking was already included in the *Integrated Product Policy of* the European Union in 2003 with a focus on ecological sustainability. [11]. The expansion towards Life Cycle Sustainability can be classified in the development of the Life Cycle Sustainability Assessment (LCSA) [10], [12]. The original scope of consideration includes the three sustainability dimensions economic, environmental, and social sustainability [12]. However, further criteria and a weighting of those can be included , so that Life Cycle Sustainability is also compatible in particular with green and economic production meeting the FESG criteria.

The implementation of Life Cycle Sustainability thus pursues the optimization - i.e. reduction - of a product's footprint considering defined sustainability criteria in accordance with Life Cycle Thinking as a goal. Thus, from a target perspective, especially in the ecological field, it is congruent with closed-loop approaches as well as the idea of a circular economy. Due to the challenge of resource scarcity with increasing global prosperity, various frameworks have emerged over time [13]. *Cradle-to-Cradle,* the *Ricoh Comet System* and the *Performance Economy* are examples of these. The representation of circularity on several levels from the product to the raw material is common for all the frameworks. The sustainable design of production is therefore often understood as synonymous with the implementation of a Circular Economy. Even though this is not completely true from an academic point of view, the strategies and technologies developed for Circular Economy are also feasible for achieving Life Cycle Sustainability. The overarching strategies can be summarized as *9Rs - Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover.* [14].

As a consequence, in the course of Life Cycle Sustainability the scope of consideration has to be extended beyond the focus on one product and one life cycle, as it seems to be implied in Life Cycle Thinking. Based on this motivation, this paper proposes a more specific definition of Life Cycle Sustainability, which explicitly includes the extension to several life cycles:

> *Life Cycle Sustainability is the objective fulfillment of defined sustainability criteria over the entire life cycle of a product, including consideration of previous and subsequent life cycles of the product itself or individual components.*

Figure 1 illustrates this understanding: Over several life cycles and use phases, a product or its components can exhibit different states. Life Cycle Sustainability is achieved when defined sustainability criteria are met across these states.

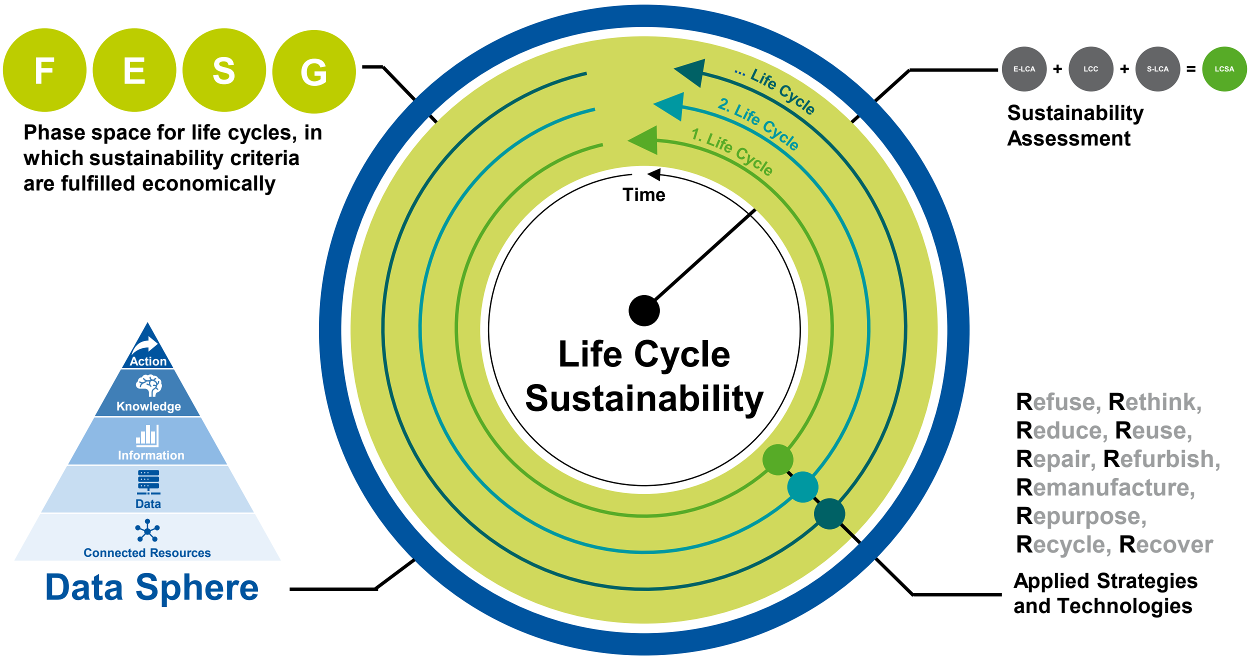

Figure 1: Expanded understanding of Life Cycle Sustainability in this paper.

Applied sustainability strategies and appropriate technologies are necessary to achieve the transition to new states that allow compliance with the criteria over an extended time. The physical life cycles are complemented by a data sphere, which is necessary in two respects: On the one hand, it enables an objective sustainability assessment using data-based indicators. On the other hand, the data is the basis for necessary information that enables targeted actions and the application of sustainability strategies.

2.2 Data-driven sustainability strategies and -assessment

To implement the 9R strategies and similar approaches, digital twins are critical and represent an enabler to leverage significant sustainability potential. [1], [2], [13]. KRISTOFFERSEN et. al. address this assumption in a review of published approaches aligned with the knowledge pyramid, which is presented in the *Smart Circular Economy Framework* shown in Figure 2 [2].

The central element of the knowledge pyramid as framework is the data flow and the corresponding data processing across all levels:

- **Connected resources** are the basis for collecting relevant data over the entire life cycle.
- **Data** is the raw form of collected information and its representation as a sign, but without context or interpretation.
- **Information** is obtained from data, e.g., through interpretation, aggregation and contextualization. Information enables descriptive analysis.
- **Knowledge** is the further conversion of information into insights and bases for decision-making and enables diagnostic or exploratory measures to be taken.
- **Actions** are the specific, possibly autonomous implementation of decision making on the basis of the knowledge gained. These include predictive and prescriptive methods in particular.

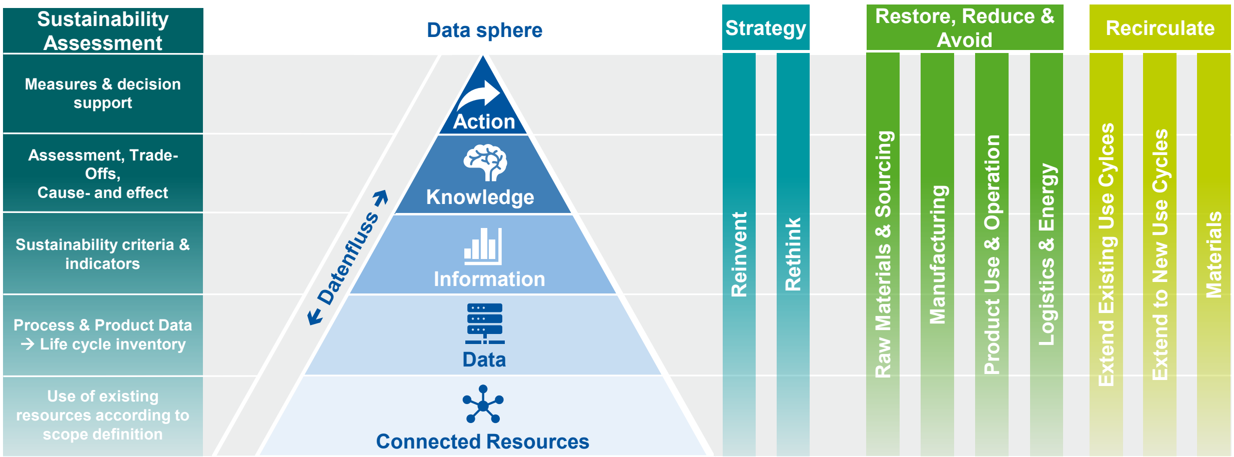

Figure 2: Smart Circular Economy Framework according to KRISTOFFERSEN *et al. [2] and levels of sustainability assessment*

The knowledge pyramid can be used as a framework for objective sustainability assessment, as it can be used to show the aggregation of available data to form indicators and assessing the fulfillment of sustainability criteria. The importance of an objective assessment can be illustrated by the example of secondary effects: While in the first life cycle it is possible to recycle most of the material used in a new product, this initially appears to be ecologically sustainable. However, if the new product addresses a need that is newly created, the footprint remains the same. A similar effect occurs when, for example, refurbishment creates a second-hand market which, however, addresses a buyer group that is disjoint from the primary market due to the lower costs. [13]. Therefore, it is necessary to quantify the scope of sustainability indicators as objectively as possible. In addition, transparent sustainability assessment is important to include customers and employees in the sustainability strategy. For example, GRANSKOG et al. suggest that by this involvement and communication, the synergy of sustainability and value creation can be adressed [15].

For operationalization, especially at the lower levels of the knowledge pyramid, the decomposition of the defined category- and criteria-specific sustainability indicators into specific quantifiable sustainability parameters is necessary so that data collection, preparation as well as processing is feasible and thus also the corresponding data structures can be designed. Figure 3 shows the categories of a sustainability *key performance indicator* model developed by SOHNIUS et al. which represents such decomposition [16]. Specific parameters are, for example, the absolute material consumption for packaging in tons (ecology/material) or the fluctuation of employees (social/employment).

Considering sustainability strategies it shows that the number of available technologies and their impact are increasing in the higher levels of the knowledge pyramid. The same applies to objective sustainability assessment, which can only succeed with suitable data aggregation and processing. Moreover, in Life Cycle Sustainability, this prerequisite extends over several life cycles. The comprehensive connection of resources and the long-term and reliable availability of usable data are becoming fundamental prerequisites for the design of green production.

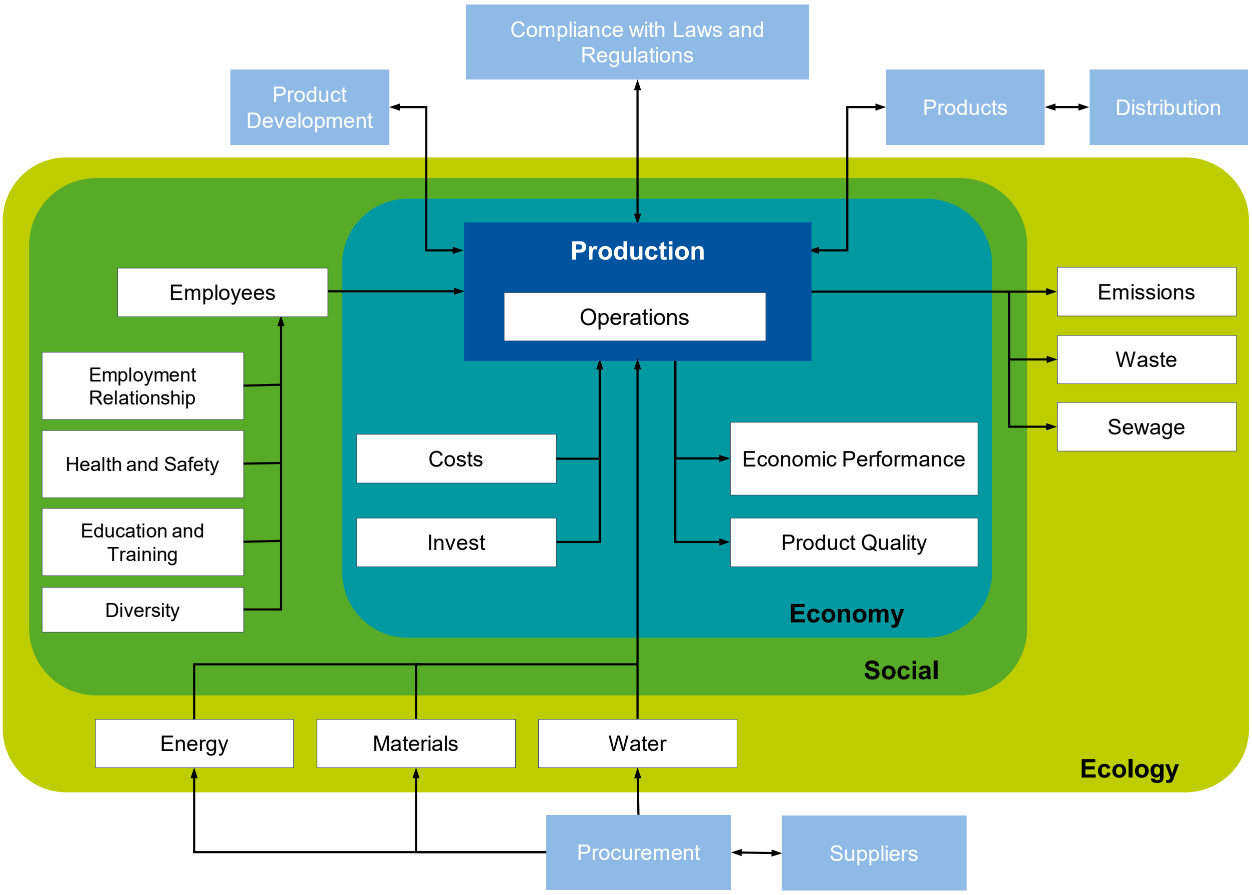

Figure 3: Categories of measurable parameters for assessing the fulfillment of defined sustainability criteria according to SOHNIUS et al. [16]

3 Resilient production data management

3.1 Resilience - definition and challenges

Resilience is a term defined in several scientific disciplines and connoted with different properties. In the field of production engineering, it is generally understood to be the ability of a system to return to a value-adding state within a certain recovery time in the face of a disturbance or other unexpected shock. [4]. In addition, resilience is often associated with characteristics such as robustness, flexibility, mutability, and agility [17].

For the goal of resilient Life Cycle Sustainability, the authors suggest defining the concept of resilience as follows:

> *Resilience in Life Cycle Sustainability refers to the ability to continue to maintain defined sustainability criteria over the entire life cycle in the face of an unexpected event, possibly with the inclusion of a limited additional footprint.*

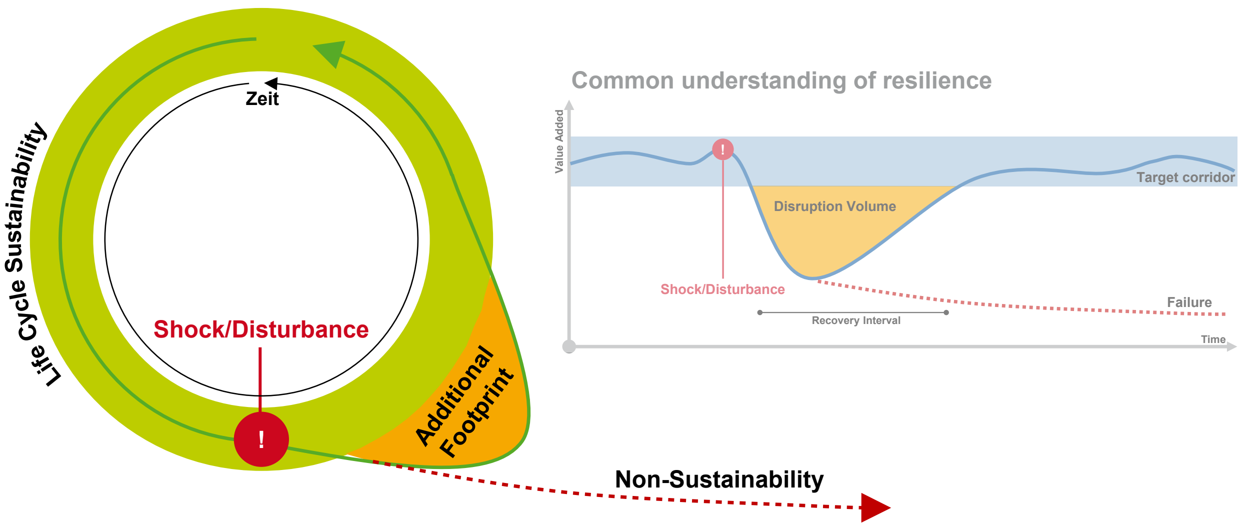

Figure 4 : Reinterpretation of the concept of resilience for Life Cycle Sustainability

This re-interpretation transforms the linear understanding of resilience into a circular target corridor that may extend over several life cycles (cf. Figure 4).

Since essential technologies and strategies for achieving Life Cycle Sustainability are data-driven (cf. Section 2), the following specific challenges for data management, among others, arise in relation to resilience:

1. Data availability itself must become resilient in the sense that a lack of availability at the moment of application of data-driven technologies must not itself become a disturbance.
2. Data must be kept in a suitable form so that a technological response can be made quickly and with a limited footprint in the event of a disturbance. This applies not only to the availability of the data itself, but also to its processing along the knowledge pyramid.
3. Possibilities for collecting necessary but previously non-existent data must be considered, for example, based on measurement technology.
4. For decision making, data must be appropriately available to assess the response in terms of additional footprint and long-term achievability of sustainability goals.
5. Data management must be ensured over very long-term periods.
6. The implementation of data management itself, in particular the storage and processing of data, brings its own additional contribution to the footprint in the sense of Life Cycle Thinking.

These challenges culminate, on the one hand, in the need to establish production data management as an independent task and, on the other hand, in the adaptation or expansion of existing areas of production technology, such as quality management and automation.

3.2 FAIR Data and FACT Algorithms

The processing and aggregation of data along the knowledge pyramid requires their interpretation without doubt or error. This is the only way to ensure that inconsistency of different data can be detected and wrong decisions can be avoided [18], to strengthen the resilience of Life Cycle Sustainability. A sufficient amount of documentation by means of metadata and contextual information on collected and stored data is therefore a basic prerequisite for finding, understanding and (re)using this data, as well as making decisions based on the knowledge derived from it. In 2016, this starting point led to the "FAIR Guiding Principles" for data presented by WILKINSON et al. [19]. "FAIR" here is not to be understood in the conventional sense, but as an acronym of the terms for the four pillars of sustainable data management: *findability, accessibility, interoperability,* and *reusability,* cf. Figure 5. Broken down into several aspects of the four principles, WILKINSON et al. formulate the following requirements:

Findability - To be able to use data at all, it must be possible to find data first. This requires, on the one hand, unique and persistent identifiers for data. On the other hand, the data must be described using detailed metadata, which enables both humans and algorithms to find this data using appropriate search queries. Technically, this means that both data and metadata are managed in a searchable index, such as a database.

Accessibility – Second, if data can be found, it must also be accessible. This does not mean that data must be freely available, but that the access rules must be communicated clearly and transparently, i.e., it must be comprehensible who can access the data and under what conditions. At the technical level, this requires the use of standardized and open data formats and data exchange protocols, as well as the technical connectivity to the storage resource.

Interoperability - Interoperability requires the data to be universally understandable and interpretable. The core aspect is the use of known and defined terms and languages for the representation of the data (or the information contained therein). Furthermore, the interoperability of data can be significantly increased by referencing other metadata and data, i.e., placing them in a larger context.

Reusability - Compliance with the aforementioned three criteria is necessary to be able to use data at a later point in time but is not sufficient on its own. To decide whether data can be (re)used for a specific application, information about the provenance of the data and all relevant attributes must be available. Compliance with domain-specific community standards and requirements and the specification of a usage license are elementary.

If data is collected, managed and stored in accordance with the FAIR principles, the data management itself also fulfills sustainability aspects. Data for which no or little information about its context is stored cannot be unambiguously interpreted and thus cannot be (re)used. Such data can therefore be considered lost [20] and, if nevertheless stored for the long term, represent an additional and avoidable footprint.

The aggregation and processing of data along the individual levels of the knowledge pyramid involves a large number of algorithms and software modules, which may also include machine learning methods. In order to achieve resilience of the derived decisions in terms of resilient Life Cycle Sustainability, not only the underlying data must be interpretable, more precisely FAIR, but also the algorithms processing the data must be correct and comprehensible [22]. This ties in with the criteria for responsible data analysis that VAN DER AALST et al. [21] present based on four conditions: Fairness, Accuracy, Confidentiality, and Transparency, cf. Figure 5.

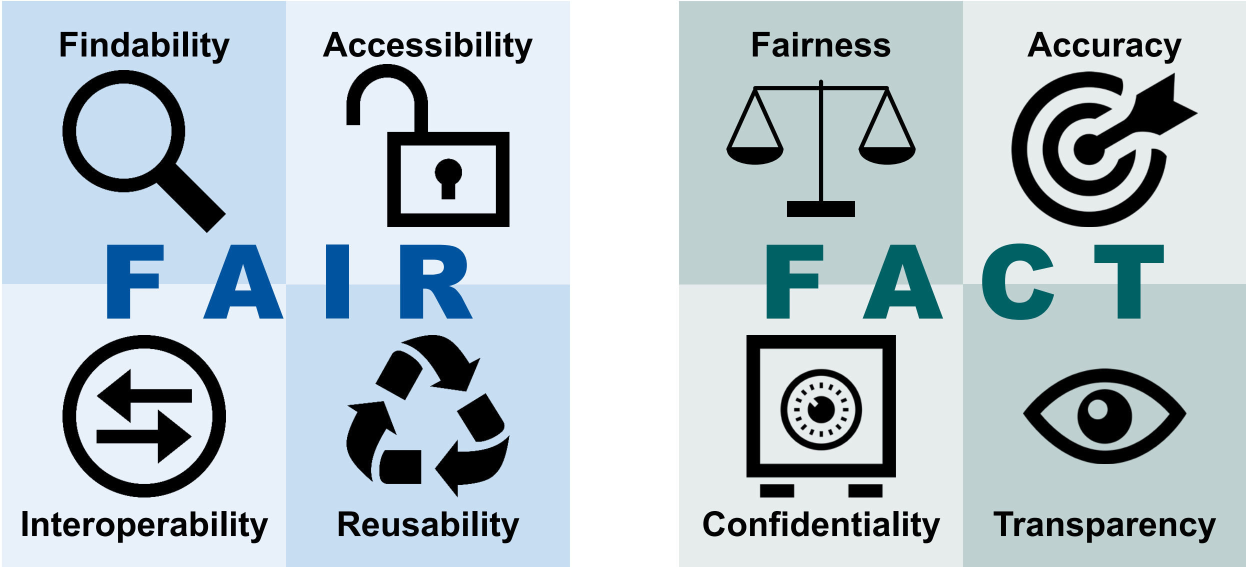

Figure 5 Left: the "FAIR Guiding Principles" for data. [19], right: Challenges of responsible data analysis [21]

Fairness – Fairness does not refer to the underlying data and FAIR principles, but to algorithms used and requires that they are unbiased. This means that both the data basis used for the training and the implementation of the algorithm must ensure that the data evaluation is not biased.

Accuracy – Due to the high-dimensional data spaces and heterogeneous input data of complex algorithms and software solutions, the precision of a result in the sense of the accuracy and reproducibility of a calculation, is often not comprehensible. Therefore, it is important to determine and return not only a result, but also an indication of its accuracy and, if necessary, the sensitivity to changed input variables. This definition often includes the concept of correctness, i.e., the property of how accurately a specific situation is represented algorithmically. A distinction must therefore be made between "accuracy" and "correctness" in the more specific sense.

Confidentiality – Processed data may contain sensitive information. To ensure data sovereignty, results calculated by algorithms must not allow any conclusions to be drawn about this sensitive input data. Similarly, a result must not allow any conclusions to be drawn about the technical implementation details of an algorithm, because the algorithm itself is intellectual property. Ensuring the confidentiality of both the data and the algorithms is therefore an integral part of responsible data analysis.

Transparency – Finally, the methods used must be transparent so that the calculated results are comprehensible. Algorithms must not be viewed and used as a black box, otherwise the results cannot be understood by humans. Transparency is not a contradiction to confidentiality, but the parallel realization of both requirements is a great challenge.

3.3 From FAIR and FACT to production data management

Establishing production data management based on FAIR and FACT holds great potential for achieving Life Cycle Sustainability resilience but is a major challenge due to the technical and organizational constraints in production. Looking at the data life cycle in production (Figure 6), it becomes clear that FAIR and FACT have comprehensive significance and must be taken into account in almost all stages of the data life cycle.

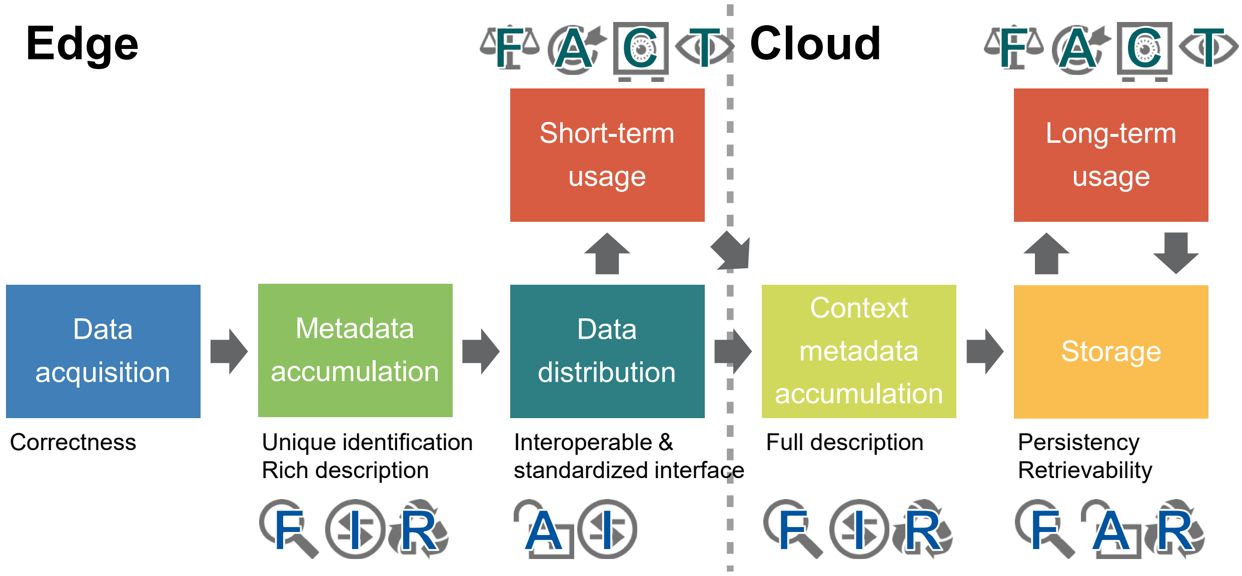

Figure 6: The FAIR data lifecycle according to BODENBENNER et al. [23]

One of the core problems in implementing the FAIR principles is heterogeneity. For example, there is not only a very large set of very different (measurement) systems for capturing data and correspondingly different models and formats for representation, but also an equally heterogeneous group of stakeholders as well as possible data-driven applications, each of which has different requirements for the data [24]. The challenge is therefore not only the technical standardization of used models, formats and protocols for storing and transmitting the data (accessibility & interoperability), for which many approaches already exist, such as the use of open, standardized protocols and formats, for example OPC UA, MQTT or JSON and XML. Critical for the long-term use of the data is especially its contextualization [25]. Long-term usage requires annotation through meaningful metadata and linking with other data so that data can be found and evaluated for usability (findability & reusability). The central challenge is to manage data accordingly and to enable findability for any applications and scenarios, some of which are still unknown. Simply storing all captured data because it might be relevant one day is not a sufficient solution. On the one hand, this data must also be contextualized, otherwise it cannot be transformed into information or knowledge, and on the other hand, storing the data in central data stores, such as cloud systems, consumes a large amount of energy. Data storage therefore itself has a significant footprint, which should be reduced to a necessary minimum in order to meet the target values of the sustainability criteria and thus achieve Life Cycle Sustainability. Another challenge is that at the time of data collection, the specific use in the long-term perspective is not yet known and suitable data sets need to be identified in retrospect. Key to this is the storage of context data, even beyond the period of storage of the actual (measurement) data. Primarily, only the contextual information is necessary for evaluating the usability of a data set, not the data itself [19]. Since context information usually has a much lower rate of change than the data itself, this can initially reduce the data footprint. Data richly documented using context information can be reproduced, if needed, or data that is not (no longer) available can be collected again based on the stored context information. Another possibility is the synthesis of suitable data.

Data-driven insight in production is increasingly based on service-oriented applications rather than monolithic software systems. Components of these applications are usually composite IT systems that also include platforms from external companies, such as cloud systems, and multi-tier architectures [26]. In particular, the role of service providers, which offer processing of data and provision of analytics and recommended actions, is steadily increasing [27], [28]. This initial situation leads to a manifold trust issue: from the point of view of the producing company, the data used is highly sensitive, as they may allow conclusions to be drawn about trade secrets or even represent them itself [29]. For software service providers, control over the use and secrecy of the implementation details of the algorithms used is essential to secure the business foundation [30]. *Confidentiality* is thus a substantial prerequisite for data sovereignty.

However, this is contrasted by the requirement for *transparency*. Data processing must be transparent and comprehensible in order to be able to secure and responsibly shape decisions derived from it. Furthermore, this is the only way to ensure an objective evaluation of measures against selected sustainability goals [31]. In addition, the uncertainty of the information obtained must also be considered in order to estimate the risk of decisions based on this information.

In metrology, for example, the measurement uncertainty associated with the measured value is the most important criterion for the quality of the measurement [32]. When measurement data is processed by algorithms, this information is often lost because the contribution of any algorithm to the uncertainty of the result is difficult to determine or may not be determined at all. The criterion of transparency in the context of production data management must therefore also include ensuring the correctness and accuracy of algorithms.

The FAIR and FACT principles set out important design guidelines that should also guide production data management. This applies in general and in the perspective of resilient Life Cycle Sustainability, which focuses on long-term requirements and trustworthiness. However, since FAIR and FACT originate from research data management, they cannot simply be adopted, but must be adapted to the domain-specific characteristics of production technology. This is especially true in complex value networks where customer, supplier, and competitive relationships exist and data sovereignty is economically critical.

4 Data structures and technological solution modules

The establishment of production data management as a prerequisite for Life Cycle Sustainability is neither a singular field of action, nor can a single, universally valid implementation be expected. Rather, it is the integration of interdisciplinary, data-driven technologies and methods in the dimensions of people, organization and technology in several fields of action. The following are examples of some of these with reference to the challenges mentioned in Section 3:

- **Quality management** must be expanded to include consideration of sustainability strategies that are already known a priori (e.g., repair or remanufacturing by the original manufacturer). This also applies in particular to the management of data whose necessity for technological implementation or sustainability assessment is known (cf. challenges 4, 6).
- Techniques of data management as well as data processing, summarized as **information management,** must be further adapted or developed specifically for production. This is particularly relevant to ensure the flow of data in the sense of the knowledge pyramid, even if the technological design of sustainability strategies and thus the data consumer is not known a priori. Furthermore, the amount of data,

the long-term nature of Life Cycle Sustainability, and the data management's own footprint introduce additional requirements (cf. challenges 2, 5, 6).

- **Sensing** can be understood as the acquisition of necessary information for which the necessary data is not or no longer available. On the one hand, this includes the consideration of measurement technology as an enabler for the targeted, situational collection of data (e.g., condition assessment), but also a further interpretation of the term to include the collection of customer feedback or field data. In addition, metrology as a discipline contributes essential aspects of long-term physical trustworthiness of collected data (cf. challenges 3, 5)
- A suitable **data infrastructure** is becoming an unavoidable prerequisite as the backbone of data-driven technologies. However, in addition to questions of compatibility, scalability and cost-effectiveness, the focus is also on the resilience and sustainability of the infrastructure itself (see challenge 1).
- **Automation** takes on a broader meaning in the target picture of resilient Life Cycle Sustainability. It can increase the responsiveness, cost-effectiveness and social compatibility of technological solutions, for example in the context of automated disassembly. However, this also requires inherently data-driven automation. (cf. challenge 2)
- The **qualification of employees** and the establishment of sociotechnical ecosystems are necessary since the production systems being created will be of considerable complexity. The participating actors must be enabled to make data-based and objectified decisions in the sense of Life Cycle Sustainability (cf. challenges 2, 4, 6).

Suitable models and corresponding data structures are characteristic, recurring elements in the fields of action mentioned. In the following, these are concretized by means of technological solution modules as examples. These extend across all layers of the knowledge pyramid.

4.1 5G as infrastructure (Connected Resources)

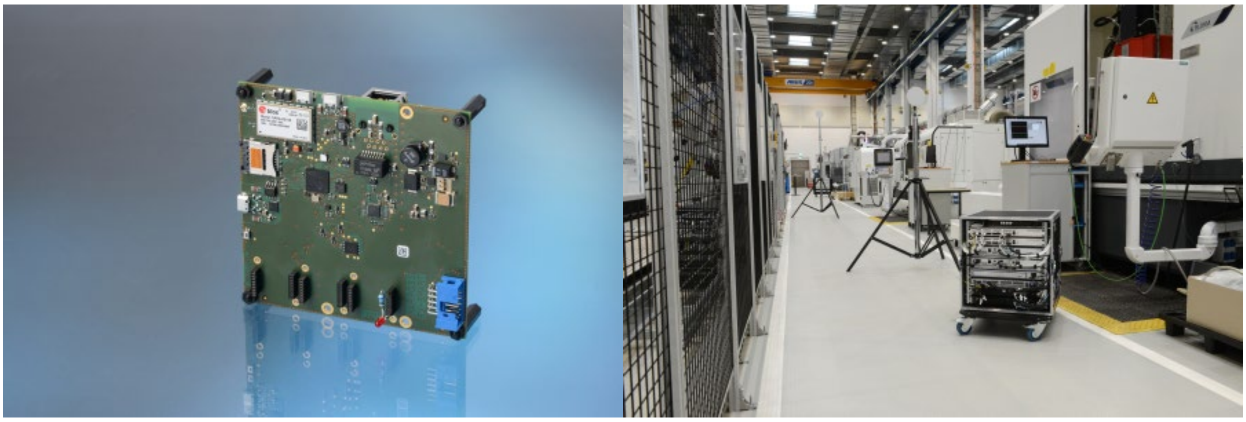

Figure 7: Left: Electronics board for 5G-based networking of sensors. Right: Local test setup for the evaluation of 5G use cases in production. Image credit: Fraunhofer IPT

Industrial communication, especially in automation, has always been associated with high requirements in terms of reliability, availability and real-time capability. The establishment of data-driven technologies in production engineering, but especially the aspects of flexibility and adaptability of automated systems, additionally transfer these requirements to wireless communication. In addition, there are the requirements for the resilience of cyber-physical production systems, which are summarized by SCHMITT et al. as follows: Decentralized IT structures, data security, modularity of technical systems, convergence of shopfloor and office IT, and integration of humans into sociotechnical systems [33]. At the network layer, there are also technical requirements for the resilient design of the communication networks themselves, as summarized, for example, by the VDE in a position paper [34].

5G is a key technology that can address the above requirements and serve as the backbone of a suitable infrastructure for connected resources. It is also connectable to other network technologies through its convergent design. The various profiles are suitable for mapping the connection of resources for several aspects of data-driven sustainability:

- It's nature as a mobile communications standard enables location-independent connection and thus the collection of data in the field, e.g., during the use phase of the customer life cycle.
- The application profiles eMMB (enhanced mobile Broadband) and mMTC (massive Machine Type Communication) are suitable for communicating large amounts of sensor data with high bandwidth or a high number of sensors. MOHANRAM et al. validate the industrial applicability using a multisensor platform based on an STM32 as an example [35]. This contains interfaces to strain gauges, accelerometers, and temperature sensors for monitoring purposes and is shown in Figure 7.
- The combination of 5G and time-sensitive networking enables the realization of wireless automation networks. KEHL et al. demonstrate this approach for application in mobile robotics and show that jitter (99.9% interval) can be reduced to below 1µs, achieving real-time capability [36].

The decision whether connecting resources via 5G is worthwhile compared to other technologies must be made depending on the expected benefits. KIESEL et al. present a model for the techno-economic evaluation of latency-critical applications with respect to the target criteria flexibility, mobility, productivity, quality, security, sustainability and degree of utilization [37]. This approach can be applied to the technological implementation of data-driven sustainability strategies in the sense of Section 2 and the goals of Life Cycle Sustainability.

4.2 Domain-adapted data structures (Data)

To ensure that data can be found and retrieved quickly in the event of a disturbance to life cycle sustainability, data must be stored in an indexable and easily searchable structure. The basic prerequisite for this is the transfer of FAIR principles to production technology on the basis of specific requirements and the technical realization of these. In addition to the use of a uniform description language (cf. Section 4.3), it is necessary to use standardized data models, formats and data exchange or communication protocols [38] (cf. Section 3.3). For this purpose, standardized solutions known from computer science can be adapted for use in production engineering. The spectrum of available solutions ranges from specific solutions for one of the three aspects to "all-in-one" solutions, such as OPC UA. Table 1 shows an overview of different models, formats and protocols. However, the data models may be tailored to different use cases, so that usually more than one data model has to be implemented in order to keep data available in required models, which significantly increases the implementation effort. Second, most models are complex and therefore require advanced data modeling skills. In addition, the majority of these models do not take the FAIR principles into account.

Table 1: Examples of standardized data formats, data models and communication protocols for use in production engineering

Model	Format	Protocol
Asset Administration Shell	JSON	HTTP
Digital Calibration Certificate	XML	MQTT
OPC UA (via XML and TCP/IP)		
MTConnect		

An infrastructure and data structure that allows the definition of measurement system interfaces with little effort has been presented by MONTAVON et al. [39], [40] and was further developed by BODENBENNER et al. [41] into a domain-specific modeling language. All properties and data of a measurement system can thus be represented by means of four different elements: Variables for the representation of measured values, parameters for adjustable property values, functions for the execution of complex procedures and objects for the structuring of all properties. Each element requires the definition of specific prescribed attributes by means of which technical interoperability with other systems can be ensured. For variables and parameters, these attributes include the permissible range of values, the mathematical dimension and also the physical unit. Since all these attributes are always provided together with the actual measured value via the interface, these values can be processed without prior knowledge. For example, suitable storage or table structures of databases can be built and managed automatically and efficiently. Figure 8 shows such a data package. In addition, the data model can also be translated into more complex structures, such as OPC UA or the Asset Administration Shell.


```
{
   “covariance”: [
         [1.3276206530821578e-10, 1.0791437929694123e-11, 7.9915972948561065e-11],
         [1.079143792969412e-11, 5.5091565613752213e-11, 1.0896977314156854e-11],
         [7.9915972948561065e-11, 1.0896977314156854e-11, 5.9079887330941402e-11]
      ],
   “datatype”: “double”,
   “description”: “Position in Cartesian Coordinates in meter.”,
   “dimension”: [3],
   “hash”: “3a785573eecfc75434572906c31bae675f1c173612bc25579c996bddf4e51a85”,
   “label”: “Calibration of machine tool.”,
   “name”: “Position [m]”,
   “range”: [-40, 40],
   “timestamp”: “2022-06-13T11:27:15.046550Z”,
   “unit”: “MTR”,
   “uuid”: “MEA-Position”,
   “value”: [2.4184784967537318, 0.32977268925781256, -3.8299400458421968]
}
```


Figure 8: Structured data package for the interoperable exchange of measurement data according to [23], [40], Figure taken from [38]

Interoperable interfaces and systems contribute significantly to the resilience of the data infrastructure of production systems, since (partial) failures of devices or subsystems can be replaced with little effort by other, but not necessarily identical, devices or subsystems. They also lower the technical hurdle of implementing a Life Cycle Sustainability assessment that is as automated, data-driven and timely as possible.

4.3 From data to information management by means of contextualization (Information)

Data can be aggregated into information in two main ways:

Contextualization - By describing data using metadata or metainformation, data can be interpreted and placed in a larger context. A simple example of this is the physical unit, without which measured values could be interpreted differently in different countries.

Data evaluation - By means of the processing a dataset by algorithms, correlations of data can be uncovered and thus allow human interpretation. For example, the individual position data of a mobile unit can be combined to form a path and the deviation of the movement can be determined by comparing the aggregated path with the nominal data. This information can then be processed accordingly.

Algorithmic analysis of data is increasingly performed using machine learning methods. However, designing these according to the FACT principles and with an appropriate footprint is a major challenge [42]. Moreover, machine learning alone does not achieve information management in the long-term perspective.

Contextualization initially represents the lighter-weight approach here and can also increase the efficiency of data evaluation as a preliminary stage. In addition, contextualization can also reduce the footprint of data management itself: Especially in the case of high-frequency data, which implies a large footprint if stored. In contrast, the storage of contextual information, which makes the reproduction of the data possible, can significantly reduce the footprint. The prerequisite for this is that the data can be generated in a short time with a small footprint. By defining FAIR data models, information management can be synergized with data management because describing data with contextual information is a fundamental principle of FAIR. FAIR data can be contextualized into information reliably in the long term.

Since data is increasingly collected, processed and stored in massively distributed systems as the degree of connectivity increases, the subsequent contextualization of data becomes more difficult. It is therefore crucial to annotate data with metadata and available contextual information as early as possible, at best at the device or edge level.

This approach was presented by Bodenbenner et al. among others and builds directly on a unified data structure as presented in section 4.2. The authors present a multi-layer software architecture for *FAIR Sensor Services that* ensures both technical interoperability of data and semantic interoperability of information on measurement data. For this purpose, the software of the cyber-physical measurement system is divided into three layers, as shown in Figure 9. The bottom layer (**L1**) covers the device-specific and non-generalizable implementation of the internal system logic. The middle layer (**L2**), the so-called "FAIRification layer", enriches the data based on the SOIL model with meta-information, such as the physical unit. The top layer (**L3**) implements the communication interface and makes all data and metadata available in a standardized data format via protocols that are also standardized. **L2** and **L3** can be implemented based on the SOIL metamodel independently of the specific device. This is made possible by adapting model-based software development, where a simple model for the interface of a measurement system can be defined, using the "SensOr Interfacing Language (SOIL)" [41]. This model can then be used for the automated generation of the FAIRification layer, as well as the appropriate interface and the desired data format [23].

As a result, measured values are immediately available as information already and not only in the form of a date. This increases the availability of the measured values in the event of a disturbance of the Life Cycle Sustainability. It also prevents the storage of undocumented and therefore hardly usable data.

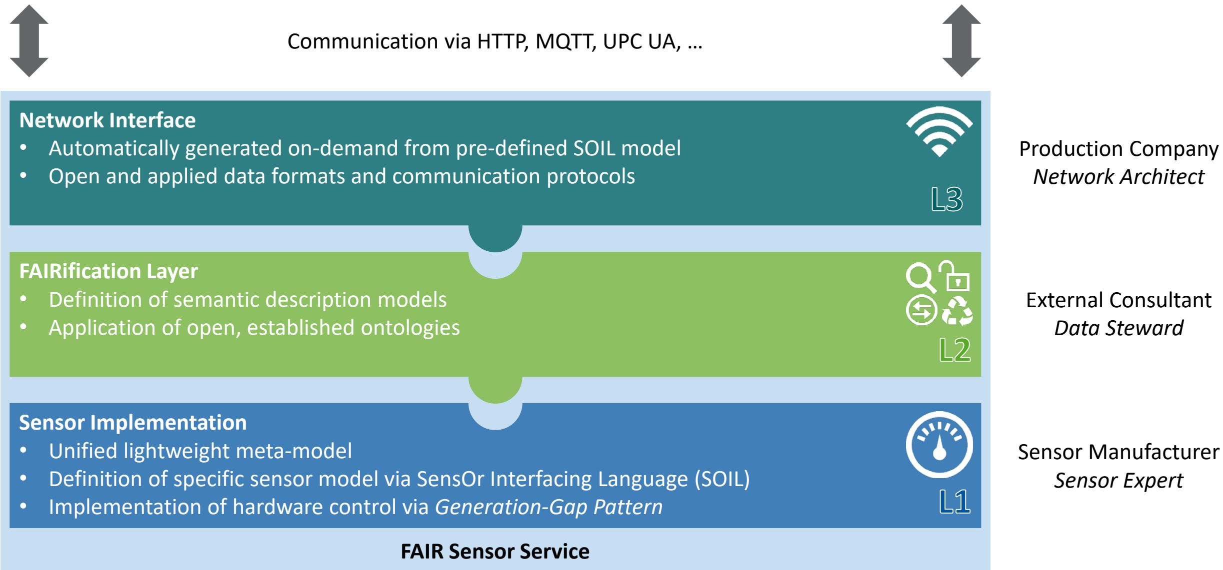

Figure 9: Software architecture of a "FAIR Sensor Service

4.4 The Digital Twin as an enabler for automation (Knowledge)

Data-driven automation requires powerful data structures that take into account both the short-term horizon of performing the specific operations themselves and the long-term horizon in terms of Life Cycle Sustainability. In addition, a balance between standardization and use-case specific flexibility is necessary to harmonize interoperability and complexity of the implementation. Here, the domain-specific adaptation of data structures based on more widely used standards is a suitable approach. For this purpose, GÖPPERT et al. present a *Digital Twin Pipeline* [43]: The first goal is to create a domain-specific ontology. First, standard ontologies and metamodels that are generally suitable for the domain are analyzed. These are then adapted to the expected use cases by means of expert input through combination and/or conformal extension. The resulting ontology provides syntax and semantics for modeling the specific use cases, an example of which is shown in Figure 10. From this model description, which is interpreted as a Digital Twin, generative programming can be utilized for the deployment of an automated system. Moreover, the ontology-based modeling can be used for persistent, reusable and interoperable management of use-case-related information in the form of knowledge.

GÖPPERT et al. evaluate the Digital Twin Pipeline for the control of line-less assembly systems. The reference implementation builds on MASON and BOT as general ontologies, which are combined with SOIL and the Asset Administration Shell as meta-models. The model obtained in the description phase is mapped using JSON as a markup language so that it can subsequently be loaded in different software environments [43]. KAVEN et al. integrate this approach into a control system for line-less assembly of a battery pack. Here, an MQTT-based, VDA 5050-compliant communication structure between the control system and automated guided vehicles is generated from the Digital Twin [44].

The Digital Twin Pipeline is a key enabler for the technological realization of line-less assembly systems. These in turn contribute to Life Cycle Sustainability through their inherent capabilities to address resilience and sustainability [45].

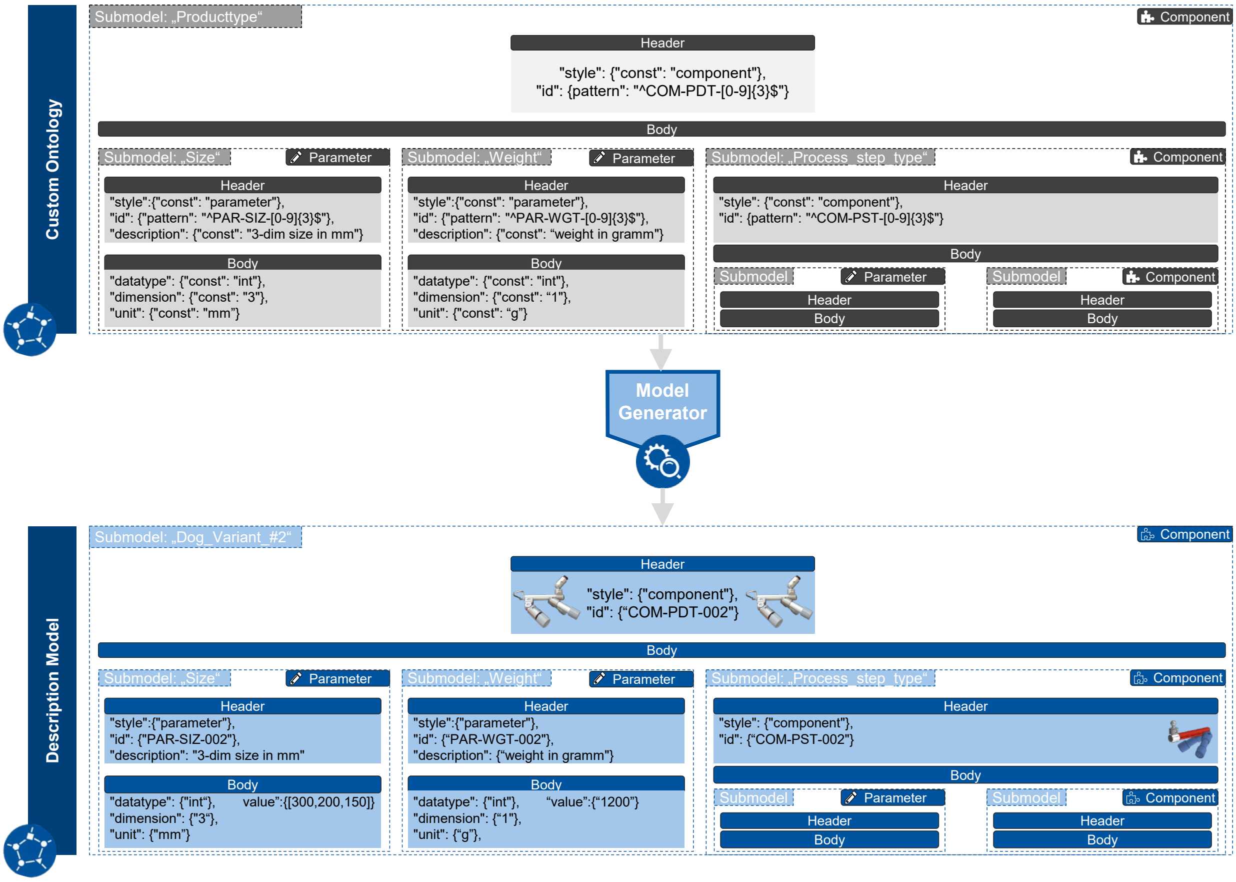

Figure 10: Ontology and description model formulated based on it for a product to be assembled. [43]

4.5 Synergies of sustainability and quality management (Action)

The challenges of sustainability management as well as quality management can be classified in the dimensions of normative, strategic and operational management according to BLEICHER [46]. In the perspective of the Aachen Quality Management Model (ACQMM), this is considered in corporate quality, which is understood as *momentary degree of overlap of market demands, business orientation and business capabilities* [47]. Sustainability goals thereby become market demands. The ACQMM also includes the Quality Stream as a central element, which represents the quality-related value stream and is oriented to the product life cycle. This provides a direct link to the goal of Life Cycle Sustainability. Quality and sustainability management can be integrated by incorporating suitable strategies for achieving strategic sustainability goals and KPIs as well as sustainability assessments into the Quality Forward or Backward Chain(s).

Figure 11 shows an approach for embedding sustainability management in the ACQMM. The consideration of the product life cycle is explicitly given by including selected R strategies (cf. Section 2). Additionally Life Cycle Thinking is addressed by the focus on the integration of data management, both vertically and horizontally.

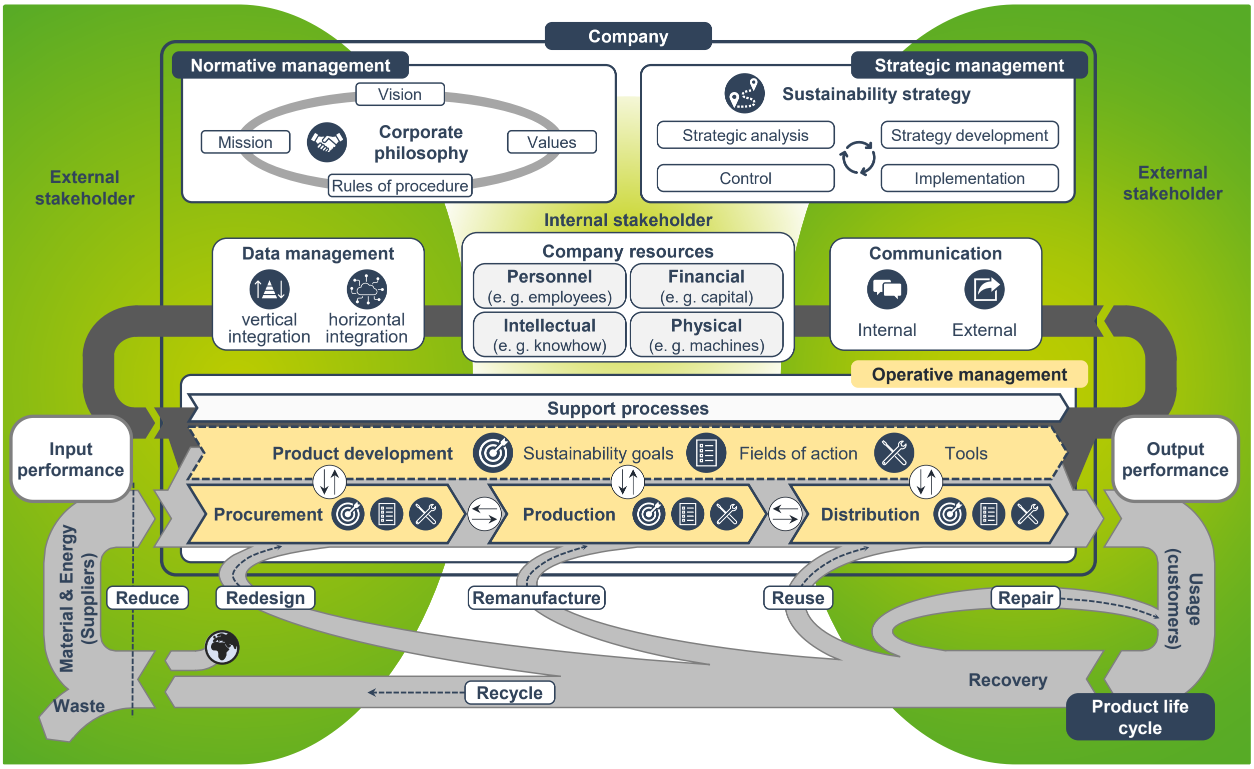

Figure 11: Incorporation of sustainability strategies into quality management in the ACQMM. [48]

From the perspective of the knowledge pyramid, the described extension of the ACQMM allows to map the action level to the previously mentioned management dimensions. Nevertheless, the complexity of the possible measures and solutions as well as the need for an objective sustainability assessment call for data-driven decision making in order to act in terms of Life Cycle Sustainability. BRIELE et al. concretize this data-driven aspect and emphasize the importance of quality and sustainability management in the further development of the *Internet of Production* [49].

5 Outlook

Data is a key driver of many technologies for achieving sustainability goals in production engineering. It is not only the collection of data itself that is important, but above all the processing and aggregation into knowledge and actions. In the Life Cycle Sustainability perspective presented this is particularly focused. At the same time, the technological complexity and individuality of the required processes are increasing, so that a resilient design of the processes is necessary. To illustrate this, an adapted definition of the term resilience was presented for Life Cycle Sustainability. Overall, specific requirements are thus defined for data structures and associated data management.

In the discipline of (research) data management, the sustainability and transparency of data and algorithms have already been demanded and investigated for some time by the principles of FAIR (Findable, Accessible, Interpretable, Reusable) and FACT (Fairness, Accuracy, Confidentiality, Transparency) data. However, these must be transferred to the domain of production engineering, as illustrated by the example of the *SensOr Interfacing Language SOIL*. The principle pursued in SOIL of decoupling domain-specific modeling from implementation in standardized data structures or communication protocols is representative of the maxim that the domain-specific adaptation of widespread standards is more important than the initiation of a large number of specific individual standards – this is also beneficial for interoperability and automation.

Overall, production data management can be identified as a new field of action for the successful design of green production. However, it does not stand alone, but must be closely linked to the respective domains, as has been outlined for quality and information management, metrology, communication technology, automation and qualification of employees. Among other things, the establishment of suitable data structures is based, on the following guiding questions, which can be used to transfer the partial solutions shown to new applications:

- What are the specific sustainability goals to be pursued?
- What strategies should be used to achieve these goals in the dimensions of people, organization and technology?
- What data and information will (probably) be needed?
- Which stakeholders are involved throughout the life cycle?
- Which standard data structures can be adapted domain-specifically?

With the help of strong production data management, it will be possible in the future to combine the *megatrends of sustainability*, resilience and digitalization in production technology in a synergetic and socially profitable way. To this end, the system boundaries of data management must be derived from the entire scope of Life Cycle Sustainability in the technological design as well as research and development. This reinforces an interdisciplinary and interoperable connected approach, which is reflected in the vision of the *Internet of Sustainable Production.*

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1.2 Closing the Loop with Automated Adaptive Disassembly

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Abstract

Closing the Loop with Adaptive Automated Disassembly

With the introduction of social and political requirements such as the "European Green Deal", the implementation of the circular economy is becoming a corporate task. However, its economic implementation as an answer to regulatory demands requires the adaptation of industrial processes regarding the desired degree of adaptivity to a then increasing variance of input materials in industrial value creation. Strategies such as re-manufacturing not only offer ecological potential, but also bring about an increase in resilience and thus open new economic business perspectives. Within the contribution, the importance of suitable disassembly systems including dismantling abilities for the circular economy is shown. Based on the specific challenges of the circular strategies, a target picture for economic disassembly systems is derived. Three industrial use cases show different forms of such systems. There is a need to automate disassembly while maximizing the adaptivity of the system to cope with different product states. Adaptive automated disassembly is the key enabler for this. Enabling technologies such as the use of sensors, AI or "design for disassembly", serve to implement this. From an organizational perspective, standardization is necessary to make data from production, from the user cycle and from automated condition assessments available and usable as a decision-taking foundation for adaptive processes. Consequently, the provision and analysis of the necessary data represents a central concern for the implementation of disassembly processes.

Keywords: Disassembly, automation, adaptivity, resilience, circular economy

Kurzfassung

Schließen des Kreislaufs mit adaptiver automatisierter Demontage

Mit der Einführung von gesellschaftlichen und politischen Vorgaben wie dem „European Green Deal“ wird die Umsetzung der Kreislaufwirtschaft zur Unternehmensaufgabe. Deren wirtschaftliche Umsetzung erfordert jedoch die Anpassung industrieller Prozessabläufe hinsichtlich des angestrebten Grades an Adaptivität an eine dann zunehmende Varianz von Eingangsmaterialien in die industrielle Wertschöpfung. Strategien wie das Remanufacturing bieten nicht nur ein ökologisches Potenzial, sondern bewirken eine Steigerung der Resilienz und eröffnen dadurch neue wirtschaftliche Geschäftsperspektiven. Innerhalb des Beitrags wird die Bedeutung geeigneter Demontagesysteme für die Kreislaufwirtschaft aufgezeigt. Aufbauend auf den spezifischen Herausforderungen der Kreislaufstrategien wird ein Zielbild für wirtschaftliche Demontagesysteme abgeleitet. Drei industrielle Use Cases zeigen verschiedene Ausprägungen solcher Systeme auf. Es besteht der Bedarf, die Demontage zu automatisieren und gleichzeitig die Adaptivität des Systems zu maximieren, um verschiedenen Produktzuständen gerecht zu werden. Die adaptive automatisierte Demontage stellt hierfür die zentrale Befähigung dar. Zur Umsetzung dienen Befähigertechnologien wie der Einsatz von Sensorik und KI, aber auch das „Design for Disassembly“. Aus organisatorischer Perspektive sind Standardisierungen notwendig, um die Verfügbarkeit von Daten sowohl aus der Produktion, dem User-Zyklus als auch aus automatisierten Zustandsbewertungen als ein Entscheidungsfundament für adaptive Prozesse nutzbar zu machen. Die Bereitstellung und Analyse der notwendigen Daten stellt folglich ein zentrales Anliegen für die Umsetzung der Demontageprozesse dar.

Schlagwörter: Demontage, Automatisierung, Adaptivität, Resilienz, Kreislaufwirtschaft

1 Introduction

In the past, previous economic models were primarily based on a linear structure in which products are disposed of after use [1]. However, the finite nature of resources has become an increasing problem as the global demand for resources has almost quadrupled in the last fifty years [2]. Half of all greenhouse gas emissions and over 90% of biodiversity loss are caused by the extraction and processing of resources [3]. In response to the European Green Deal [4] and the goal of climate neutrality by 2050, the EU Commission promotes circular business models through actions for the circular economy [5]. The "Action Plan for the Circular Economy" requires that almost all physical goods must not only be more energy-efficient throughout their entire life cycle, but explicitly more recyclable – i.e. for reuse as secondary resources. [3], [5] Regulations are thus anchored in regulations, such as making simplified product maintenance, refurbishment, and the recycling of products. These measures are aimed at implementing the concept of a "true circular economy in the EU" through tangible actions and concrete product measures [5].

However, in 2022, the percentage of reused resources in a circular manner is only 7.2 %, while in Germany 12 % of secondary resources are reused [3], [6]. This creates a significant gap that can be narrowed by extending the lifespan of resources through methods such as remanufacturing [6]. In addition to dealing with the shortage of raw materials, possible savings potentials, customer requirements and increasing competitiveness are drivers for the implementation of the circular economy. [7]

To fully benefit from the potential of resources, it is important to not only design products accordingly for a circular economy, but also to establish the necessary processes. However, not all products are currently designed in a way that guarantees profitability in remanufacturing processes [8]. In addition to reverse logistics, the disassembly of products is a major challenge that cannot be classified as a simple reversal for assembly activities [8], [9]. The process of disassembly is characterized by a diverse range of variants, fluctuating product conditions and quantities. Despite the variants, the high demands for scalability must be met, which at the same time enables a reproducible handling of the large number of uncertainties [9]. Resolving these conflicts can be a key to utilize the necessary potential of secondary resources for a more sustainable production. The necessary change in production design must be actively supported by concepts and technologies.

This article explains how the circular economy can be facilitated by disassembly systems that enable materials and components to be returned to the production process. The article first discusses the various strategies of the circular economy, such as recycling and remanufacturing. It highlights the importance of industrial remanufacturing and presents a vision of an efficient disassembly system consisting of four key characteristics: disassembly depth, degree of destruction, process adaptivity, and system adaptivity. The article then explains the technologies associated with each of these properties, using the refurbishment of washing machines (Miele & Cie. KG), disassembly of car battery boxes (Ford Werke GmbH), and remanufacturing of leisure shoes (PCH Innovations) as examples. Finally, the article discusses the similarities between these use cases, and identifies future fields of actions.

2 Remanufacturing for the circular economy

Given the challenges presented in terms of resource availability, the dimension of "sustainability" has become an essential addition to the production optimization [10]. In order to implement more sustainable business models, it is necessary to shift the focus from the production to the entire life cycle, with special emphasis on the end-of-life phase [10], [11]. A sustainable industrial circular economy is not limited by factory gates but also takes the usage cycle into account. The scarcity of resources has become a major driving force for change, leading to an increased focus on the recovery of resources [11]. However, it is important to note that different concepts have varying definitions of what constitutes a "resource," which will be explained in the following section.

2.1 Development from the linear to a circular economy

A sustainable economy requires a comprehensive analysis that considers the environmental impact of using resources. Therefore, to fully analyze the environmental impact, the entire product lifecycle must be taken into account [10]. The traditional linear economic model assumes that products have a one-time lifecycle: raw materials are extracted, products are manufactured, and the products are disposed of as waste [1], [12], [13]. This one-time lifecycle is also known as "cradle-to-grave" [12], [13].

Design options for a sustainable production are provided by the three concepts of efficiency, consistency and sufficiency. Efficiency measures are focused on improving the use of resources in relation to the output produced, which is an ongoing task from both an ecological and economic perspective [14], [15]. However, these measures only mitigate negative effects, e.g. material savings, but do not solve the underlying problem [16]. On the contrary, the consistency approach aims to improve effectiveness by extending the product life cycle through various strategies, with the goal of reusing resources as often as possible. This concept is known as the circular economy [17]–[19]. The approach of circular economy aims to establish usage cycles that generate no waste, promote a holistic perspective, achieve complete recyclability of materials, and utilize renewable energies. Such design concepts can then also be economically beneficial. [20], [21] In particular, design concepts that proactively shape the entire product life cycle fulfil a crucial task toward this goal [16].

In literature, various strategies are discussed that focus on recovering resources, improving their value, and enabling more life cycles [22]–[24]. For instance, POTTING *ET AL.* define ten "R-strategies" [22]. Some selected terms of the "R-strategies" are listed for further elaboration (see Figure 1):

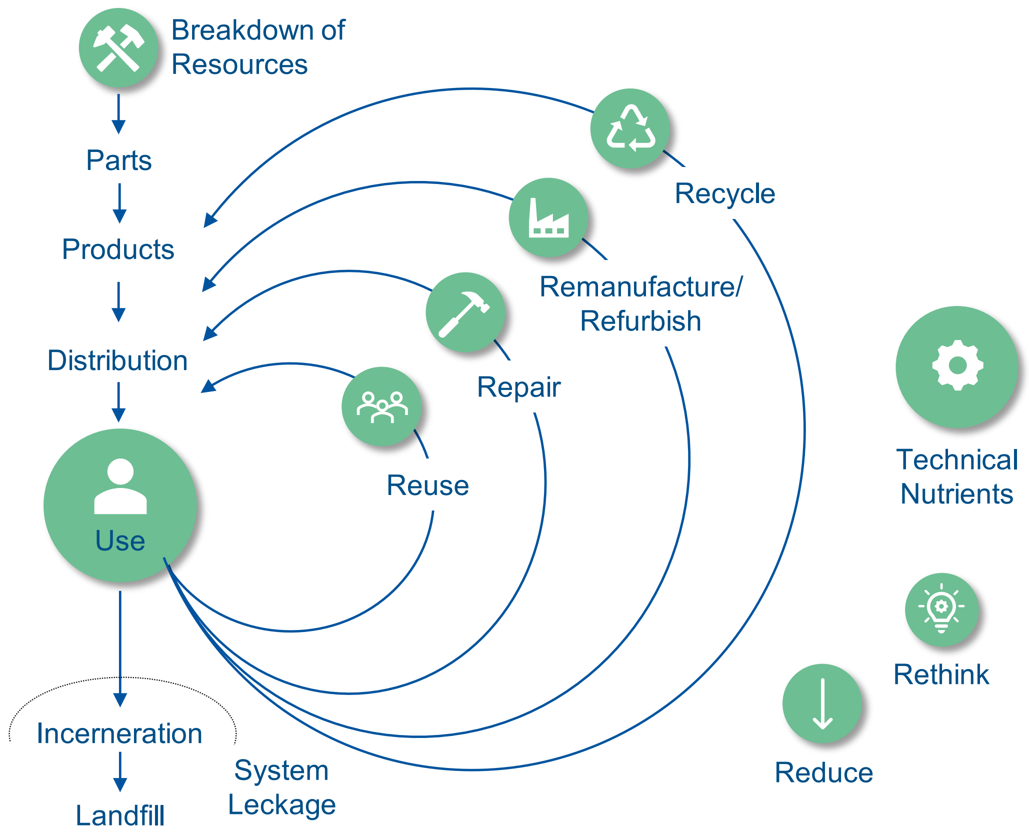

Figure 1: Industrial resource use through circular economy; based on [23]

The most established R strategy is "Recycling“ [16]. Recycling refers to the reprocessing of valuable materials [22], [25]. However, in this process, the material loses its original function and form. As a result, the product must be returned from the material phase to the usage phase, requiring many process steps to be repeated and resources must be spent. Therefore, a "longer" path is taken before the material can be used again in new products [26].

In contrast, "reuse" is a strategy with low additional material and energy expenditure. Reuse refers to the reusage of a product after it has been discarded by another consumer after its initial first-life use [22]. In contrast to recycling, this method results in a much “shorter” journey for the product back into the usage phase. In turn, the "Repair" strategy involves the additional step of repairing or servicing a damaged product to restore its original function before it is available for use in the market again [22].

If repairment is not possible, additional value-preserving measures can be utilized instead of material-conserving activities such as recycling [26]: "Remanufacturing" refers to the process of disassembling a product at module or component level and using those parts to create new products. When the reprocessing of the product itself cannot achieve the required level of functionality, the discarded components can be used in products with different functionality. [22]. These options are highly valuable for industrial use, not just because they contribute to the circular economy, but also because they offer the potential for functional improvements and value creation while the reprocessing. To implement these strategies, several tasks must be carried out, including a condition assessment, the disassembly processes, reprocessing of components for reuse, potential replacement of parts, and remounting of those parts in the original or new products. Quality inspections complete the process chain [16], [26], [27] As illustrated in Figure 1, strategies with a “shorter route” are generally preferable because faster reuse of the product and lower resource consumption can be achieved [22]. However, to achieve holistic ecological and economic advantages through "R-strategies", it is necessary to ensure that problem shifting in the life cycle is avoided [28].

2.2 Potentials and challenges of remanufacturing

According to a study by PARKER *ET AL.* , the market potential for remanufacturing in the EU is estimated to be up to €90 billion by 2030 [29]. Of particular interest is the high flexibility for the use of components in various products and, if applicable, with new technology standards [30], [31]. Refurbishment and remanufacturing represent a great potential for industrial production from the perspective of recovering resources for sustainable production and developing additional business fields. [29], [30]

Economic and ecological business models are essential for the implementation of "R-strategies" in an industrial context. However, there are several challenges that need to be addressed to achieve this.:

- Used products must be collected through the appropriate redistribution channels [16], [26].
- Products are often not designed for disassembly, leading to difficulties in achieving economic disassembly and restoration of the product [12], [26], [27].
- The high number of variants for some product groups leads to additional complexity in the remanufacturing process [32].
- The different time periods until the return of the product and the consequent different technologies during disassembly must also be addressed [33].
- High labour costs, such as those associated with manual disassembly, are a significant barrier to further expansion of industrial remanufacturing [29].
- An important challenge in remanufacturing is the accurate measurement of the condition level of each individual component, in order to apply efficiently the appropriate treatment processes [27], [34].

Automation can make the R-strategies economically feasible by enabling scalability and increased capacity [35]. At the same time, many of the challenges listed also represent demanding tasks for automation in linear concatenation, especially with regard to disassembly systems [36]. Furthermore, there is a lack of proven systems that can provide the required flexibility and versatility for allowing product-specific usage paths. There is a need to validate the scenarios through industrial applications.

3 Disassembly for economical remanufacturing

Disassembly is a central component of remanufacturing. The goal is to disassemble the product into its individual parts so that they can be checked and, if necessary, repaired or replaced. While assembly is defined as ensuring the functionality of a product by joining all components, disassembly describes the process of recovering assemblies, components, or materials from a multi-body system for further use or reprocessing. [37] Although assembly and disassembly have similar and sometimes identical requirements for kinematics and tools, disassembly cannot be understood as the direct logical reversal of assembly. [37], [38 as cited in 39] Issues arise especially from complex disassembly processes due to non-disassembly-friendly designs, heterogeneous product conditions [39], and a wide range of products and variants. To address these issues, an adaptive disassembly system needs to be implemented where the continuous development of product, process, and system technologies is necessary.

Initially, the characteristics of disassembly depth, degree of destruction, and adaptability of economical disassembly systems are presented below (see Figure 2). Subsequently, enabling technologies for economical disassembly systems, such as product, process, and system technologies, are highlighted.

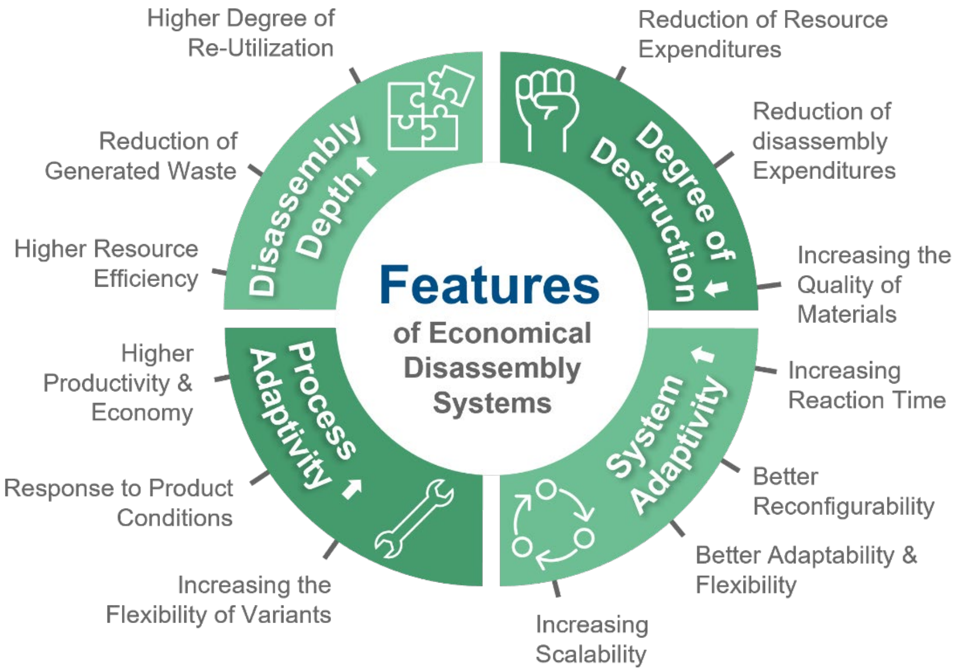

Figure 2: Characteristics of an economical disassembly system

3.1 Vision of an economical disassembly system

The **disassembly depth** is a significant measure of the efficiency and sustainability of a disassembly process. Typically, legal requirements dictate the minimum disassembly depth, which comprises all the disassembly activities necessary for the complete pollutant disposal. Conversely, the maximum disassembly depth refers to the complete disassembly of a used product. The optimal disassembly depth falls between these two endpoints and is established by taking into account the labor, cost, and residual value of the components. It also requires comprehensive knowledge of the product's condition, structure, joining techniques, and available methods for separating joints. [40] To maximize the efficiency and sustainability of a disassembly system, it is necessary to optimize the depth of disassembly. This can be achieved primarily through suitable product design that facilitates disassembly and reduces the associated expenses.

Aside from the disassembly depth, the **degree of destruction** also plays a crucial role for the economic efficiency of the disassembly process. Disassembly can be non-destructive, partially destructive, or destructive [37]. Destructive disassembly is used mainly for recycling components that cannot be disassembled non-destructively due to irreversible connections or component alterations, e.g. oxidation or damage of screw heads. [41] Non-destructive disassembly, on the other hand, is suitable for components that can be processed and reused, such as loosening screw connections or clip fastenings. Between destructive and non-destructive disassembly, there is semi-destructive disassembly**.** This is characterized by destroying the joining element while leaving the components unaffected [42]. This often serves as the starting point for non-destructive disassembly steps. To minimize the degree of destruction during disassembly and maximize component reusability, appropriate product design is essential. This not only reduces resource use during recycling but also helps to achieve an optimal disassembly depth.

In addition to the disassembly depth and the degree of destruction, the adaptability of the disassembly system is also a key factor affecting the cost-efficiency of remanufacturing. The term "adaptability" refers to the capability of making timely and forward-looking adjustments to structures and processes in a cost-effective way [43]. While a flexible disassembly system is capable of responding promptly to changes in circumstances, an adaptive system is characterized by its ability to make both short-term and long-term adjustments. Long-term adjustments usually involve more complex and resource-intensive changes to the fundamental structure, but also allowing to implement sustainability and economic efficiency of production systems for a long period of time. On the other hand, short-term adjustments are quick, efficient, and require minimal investment. Thus, flexibility describes short-term adaptability within a certain range, while adaptivity refers to the ability to transform in both the short and long term. There are different forms of adaptivity in a disassembly system, such as process and system adaptivity. Process adaptivity refers to the capacity to respond actively and rapidly to changes in circumstances by adjusting procedures and methods [44]. An adaptive process can disassemble various product types and variants, while taking into account specific disassembly requirements for each product. Adaptive processes are also crucial for disassembly of products with unknown product conditions. Unknown conditions due to contamination, destruction, aging, wear, and corrosion of components can alter process boundary conditions and require customized and adaptable processing strategies.

Moreover, an adaptive system for disassembly is characterized by its strong system adaptability, which refers to the system's capability to adjust to external conditions [45], such as the market demand or the availability of resources. One of the key characteristics of adaptive systems is reconfigurability, which allows for capacities, functional content, and technologies to be reorganized [46] in a way that system properties like production rate, product mix, or resources can be tailored to external conditions. To conclude, an economically viable disassembly system is defined by the following traits:

- Maximization of disassembly depth while taking into account cost-efficiency
- Minimizing the degree of destruction to maximize reusability
- Maximum process adaptivity for the disassembly of a wide range of products and variants and for introducing product-specific machining strategies
- Maximum system adaptivity to increase responsiveness to external influences.

Product, process, and system technologies contribute significantly to achieving economical disassembly systems (see Figure 3).

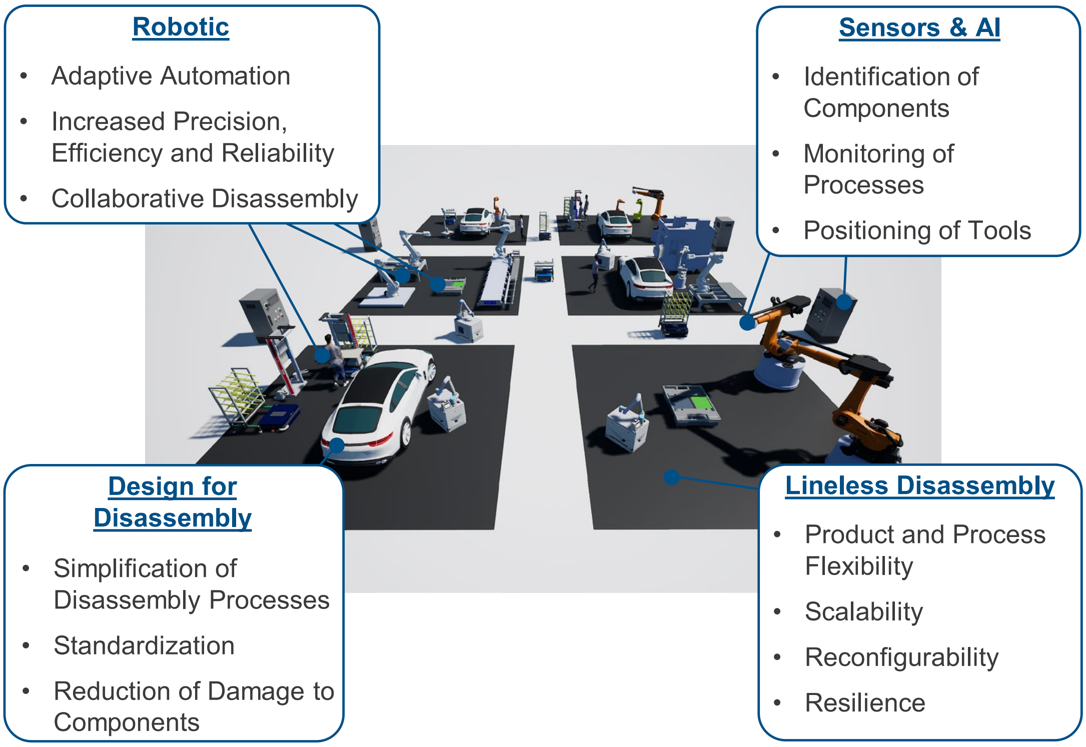

Figure 3: Vision of adaptive disassembly systems based on exemplary enabling technologies

3.2 "Design for Disassembly" - Product technology as an enabler for economical disassembly systems

Design for Disassembly (DfD) is a product design approach that aims to facilitate the disassembly of products into their individual components to enable reuse, recycling, or refurbishment strategies [47]. The concept of DfD is to design products that can be easily disassembled with little effort, while minimizing damage to the components during disassembly. The primary goal of DfD can be achieved through a variety of design techniques, including:

- modular design
- the selection and use of materials
- the use of mechanical joining technologies
- clear identification of components and materials. [48]

Modular design, as a core element of the DfD approach, aims to reduce complexity and create synergies through modular product architectures [49]. In particular, modular design of variant-rich products proves to be a promising measure along all stages of the product life cycle. In the context of remanufacturing, modular product architectures offer the advantage of standardized disassembly processes and thus, promote process automation. In addition to a modular design, the selection and use of suitable materials is very much relevant. DfD requires a comprehensive examination of the materials used to select those with low environmental impact, suitable for assembly and disassembly processes, and with high recycling potential. [48]

The use of mechanical fastening technologies such as connectors, screws, and locking mechanisms is a central part of DfD. Unlike adhesively bonded connections, these offer the advantage of non-destructive disassembly, thus increasing the number of reusable components and reducing the cost of disassembly processes. By clearly labeling materials and components, the goal is to facilitate the identification and separation of materials during the disassembly process. This allows materials to be sorted for recycling or reprocessing, ensures the traceability of materials and facilitates the planning of future use [48].

Overall, DfD can be a significant enabling technology for economic remanufacturing, contributing to the efficient disassembly of products, reuse of components, and recycling of materials.

3.3 Robotic automation, AI development & sensor technology - Process technologies as enablers for economical disassembly systems

The automation of disassembly processes is an essential technology that can help to create cost-effective disassembly systems by improving efficiency, accuracy, and reducing errors, and subsequently, leading to lower costs. To determine the best degree of automation for the disassembly system, the factors depicted in Figure 4 should be taken into consideration.

Manual, robot-assisted, and fully automated disassembly processes can be compared based on their attributes, and advancements in AI and sensor technology improve the adaptability of disassembly systems.

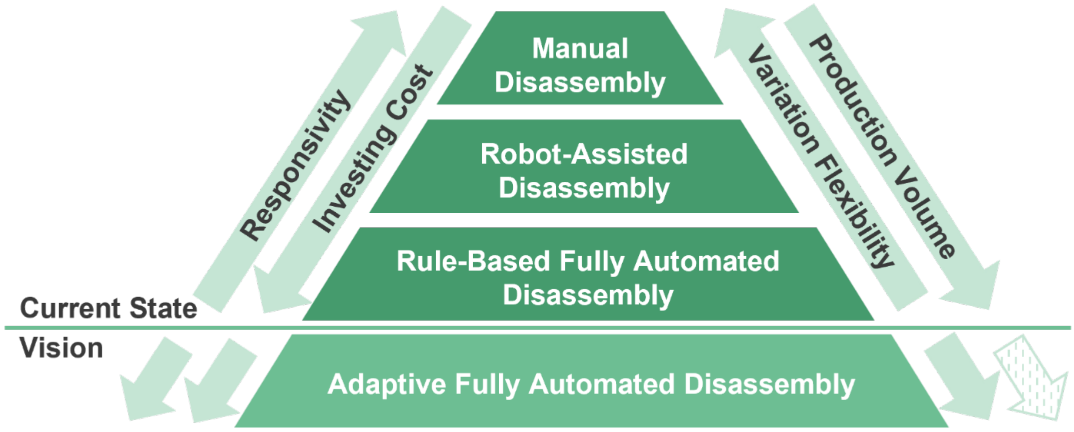

Figure 4: Factors for determining the degree of automation of disassembly systems, based on [50]

Manual disassembly is characterized by its high adaptability, as it allows to respond to unforeseen circumstances during the disassembly process [50]. Compared to higher degrees of automation, manual disassembly systems can be gradually expanded and have lower fixed costs for the operating equipment. However, lower productivity, high personnel costs, and non-reproducible quality are drawbacks of the manual disassembly when compared to automated disassembly. In particular, the identification of the individual components in cases of high product and variant diversity poses an additional challenge. To address this challenge, image-based AI systems for worker assistance can be used [51]. They support, for example, the identification of components where nameplates and serial numbers are no longer legible, or in assessing the components condition. A collaboration between staff working on the disassembly and AI systems combines the advantages of both, overcoming obstacles and difficulties within the sorting procedure, as well as reducing the error rate in product identification.

Robot-assisted disassembly is a possible extension of the manual disassembly that can increase the efficiency as well as the volume of disassembled products [11]. In robot-assisted disassembly, humans and machines work together on the object to be disassembled [52]. While humans perform more complex tasks, the robot assists in performing repetitive and time-consuming work steps. Human tasks include the separation of complex component connections, handling limp components, or performing manual inspection tasks. The robot, on the other hand, simultaneously removes screws and bolts, the position of which has been taught manually beforehand or detected via a camera and performs handling tasks. In addition to increased productivity, advantages of robot-assisted disassembly are that it reduces the workload on the human staff and exposes them to fewer risks by allowing the robot to perform tasks such as lifting heavy loads or removing hazardous materials [52].

For disassembly tasks of identical and modularized products in high batch sizes, **fully automated disassembly** systems are often the preferred option. While automated processes are already commonly used in assembly, they are still not commonly found in disassembly. However, pilot projects have shown that using SCARA and 6-axis robots for disassembly have great potentials for the disassembly system [53], [54]. The tools for automated disassembly can be categorized as handling tools or cutting tools [55]. Handling tools include vacuum or finger grippers, while cutting tools can be either non-destructive, such as screwdrivers, or destructive, such as drilling spindles and plasma cutters. Full adaptability is achieved at the process level through multifunctional tools and tool-changing systems, as well as product-specific programming and the use of AI algorithms.

The ability to adjust processes quickly is particularly important for automated disassembly processes. The **sensor capabilities** of robot-assisted and automated disassembly cells play a significant role in the development of this technology. Challenges like manufacturing tolerances, changes in geometric dimensions due to wear and deformation caused by process forces, and the increasing diversity of products and variants are significant for both, industrial production and disassembly automation. Therefore, disassembly robots must have a certain degree of decision-making freedom to perform their assigned tasks. According to NEHMZOW , freedom of choice implies the ability of the machine to determine its sequence of actions through its own inference processes, rather than following a fixed, rigid sequence of instructions from outside. As a result, a robot must perceive and interpret its surroundings, develop an action plan to handle the task, and then execute an appropriate action. [56] Sensors are used to perceive the environment and internal states of robots. They allow the robot to determine its own state, such as the position of a robot arm or end effectors, detect touches, measure distances to objects, or capture images of the environment [57]. The fusion of sensor data from various sources and their interpretation enables compensation for positioning and component deviations and generally facilitates adaptive process adjustments.

Overall, technological advancements in the areas of automation, sensor technology, and AI are making a significant contribution to replacing cost-intensive manual disassembly processes with automated adaptive processes, thus making remanufacturing economically viable.

3.4 Lineless assembly - System technology as an enabler for economical disassembly systems

Choosing an appropriate organizational structure is crucial for the effective implementation of an economical disassembly system. It defines the fundamental features of the system, such as flexibility and adaptability, as well as spatial and temporal relationships

[58]. Fluctuations in production volume, the integration of new products and processes, and high variant flexibility present unique challenges for disassembly systems.

The **takt-based assembly line** is based on a strict spatial and temporal concatenation of assembly stations. Due to the spatial linking, stations in the process can neither be skipped nor subsequently added, while the temporal linkage only allows for order passing if the following station has also completed its task. This setting results in a fixed cycle time for all stations. [36] However, the takt-based assembly line becomes less efficient with an increasing number of diverse product variants with varying work content and process times. Consequently, the takt-based assembly line is better suited for the disassembly of standard products with little product variety in large quantities. Although other organizational forms, such as **individual workstation disassembly**, **on-site disassembly**, or **workshop disassembly**, provide higher process and system adaptability, they are not suitable for economically operation of large series.

The organizational structure of the so-called **lineless assembly** method provides a remedy at this point and introduces a paradigm shift in the design of assembly systems. In contrast to the traditional assembly line, where components are guided through assembly stations on a fixed path like a conveyor belt, a lineless assembly system allows for individual guidance of each product and does not require a fixed cycle time. This approach is characterized by flexible product-specific assembly sequences and an event-based control system that coordinates the material flow and autonomously determines order routes based on the system and product state [36]. The lineless assembly structure offers advantages like scalability, the ability to reconfigure stations during operations, and the capacity to handle process variants, which makes this setting beneficial for not only assembly operations but also for disassembly systems. Because lineless assembly allows the addition of extra stations to the system easily and has high flexibility against product and process variants or disturbances, the lineless assembly structure may also appropriate for combined assembly and disassembly systems. A combined assembly and disassembly system is a system of both, disassembling products into individual parts and assembling products from individual parts. These systems are designed to enable flexible and efficient production by integrating material recovery and product recycling into the production process. This enables supplier independence and partial decoupling from global influences.

The lineless organization holds great potential for the successful implementation in both disassembly and combined assembly and disassembly systems. Above all, the synergies created, and the high level of adaptability set it apart from other forms of organization for operating remanufacturing systems economically.

4 Use Cases

The following sections, three examples from companies in the expert group are presented that demonstrate specific applications for closing material loops. The example from Miele & Cie. KG focuses on the refurbishment of washing machines, while Ford Werke GmbH aims to implement widespread remanufacturing of vehicle batteries in the future. The third use case highlights the possibilities of shoe refurbishment by PCH Innovations. These examples illustrate the current considerations of circular economy in three very different industries, which differ not only in the market but also in product design and expected return rates. The use cases discuss concrete potentials of "R-strategies", the implementation of the necessary disassembly, and the resulting challenges for the business areas are discussed.

4.1 Refurbishment processes for second-life washing machines

Starting situation

The implementation of circular strategies also represents an important perspective for established companies. With over 23,000 employees, Miele & Cie. KG generated sales of € 5.43 billion in the 2022 financial year. In its current corporate strategy, the topic of sustainability is explicitly implemented as one of the supporting pillars. In this way, Miele is addressing social challenges and the extended product responsibility, as well as the increased demand for sustainable and durable products. As the world’s leading supplier of premium household appliances as well as premium electrical appliances for commercial use, particular attention is paid to the circular economy and the associated second-life products. This is being implemented in the washing machine business case. Since the fall of 2022, the refurbishment of washing machines has been taking place in a regionally limited sales area.

Table 1: Overview Miele & Cie. KG Use Case

Company:	Miele & Cie. KG
Product:	Washing Machines
R-Strategy:	Refurbishment
Main Challenges:	Product Variance and Complexity
Most Important Enabler Technology:	Adaptive Process Automation

Objective of the use case and structure of the product

The aim of the use case is to establish the refurbishment of premium devices, promoting usage paths that align with circular economy principles. Depending on the washing machine's type, age, and condition, the refurbishment process needs to be tailored to the specific product. Suitable disassembly systems are required to achieve this goal. The potential for refurbishment is derived from the consideration that the offered washing machine is designed in such a way that after a long initial lifespan with the customer it remains functional. The product should therefore not yet be sent for raw material recycling at this stage. Thus, the refurbishing of household appliances is not only a response to future regulations on product circularity but also represents an interesting business case. In the regionally limited sales area, the share of refurbished appliances is currently still in the single-digit percentage range and is to be further expanded.

To design the required disassembly system, it is necessary to consider the product structure. Essentially, the individual washing machine remains as the product and forms the framework of the refurbishment. Various components are refurbished or replaced, and in any case, cleaned. A high degree of disassembly to the individual component level is generally not required, but accessibility for replacement is crucial. At the same time, the components should be replaceable with minimal damage.

Figure 5 shows an example of the structure of a washing machine and possible components that could be examined in the context of refurbishment. These include consumable parts such as pipes, the belt pulley, or shock absorbers, as well as the door and control electronics. This process also provides an opportunity to upgrade the device, for example, through software updates. The variability of the components and their different conditions in each device must be addressed in a refurbishment system.

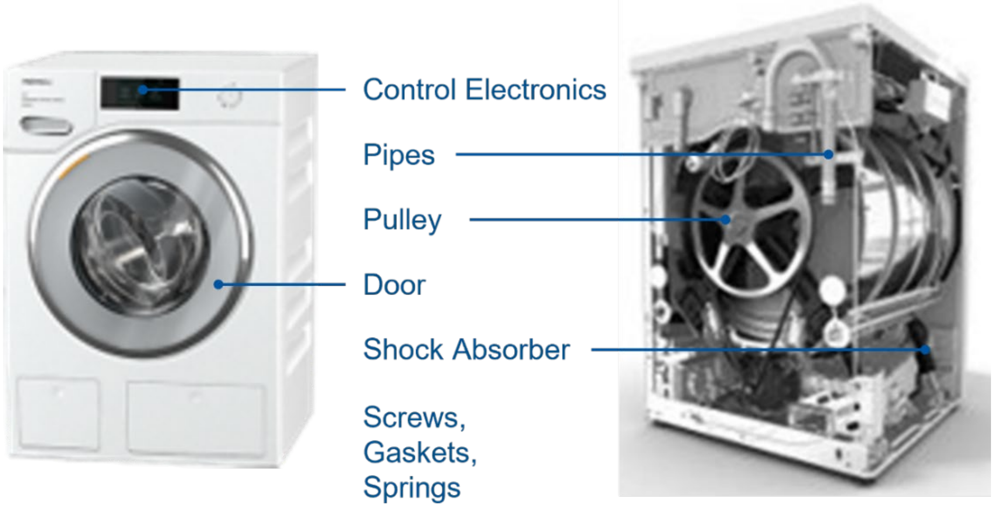

Figure 5: Exemplary selection of washing machine components that can be replaced in the refubishment process (Source: Miele)

Features of the disassembly system

Figure 6: Planned refurbishment process chain for the second-life washing machine (Source: Miele)

Condition assessment. The devices are collected centrally by the customer service department as its own logistics solution. The product condition is checked, and the technical reconditioning as well as its economic feasibility in terms of preparation time and part costs are evaluated using a proprietary software solution.

Automated assembly planning. Provided that the refurbishment process is technically and economically feasible, a detailed plan for the process is created using software support. Device-specific planning of the disassembly and reassembly processes is carried out by determining the components to be replaced. The depth of disassembly is determined based on the condition of the components, and the necessary degree of destruction is decided based on the condition of the product.

Disassembly and reassembly. The steps of disassembling, replacing parts, and reassembling follow the planning. Firstly, the previously identified parts are disassembled, among them also hygienically stressed ones. The components to be exchanged are then replaced, considering the device-specific refurbishment planning, and the washing machine is entirely reassembled. The degree of disassembly and reassembly activities fluctuates significantly depending on the product type and condition. Various ideas help to achieve the vision of adaptive disassembly systems, including a product design that facilitates disassembly. For instance, by avoiding joining connections such as adhesive processes, which reduces the costs and effort involved and minimizes the damage caused during the process. The current process configuration uses automation to a low degree, as the automation is limited to selected process steps. The manual processes' high adaptability allows to react in a flexible manner to unforeseen situations. The overall system’s high process adaptivity is currently the primary reliance. At the same time, the system adaptivity, such as adjusting the production rate, has currently a low priority, as the presented use case is quite new in its development.

Software Update. After successful reassembly, the software of the washing machine is updated. Depending on its age and equipment, this may also lead to an increase in value to the washing machine.

Automated functional tests. In the following process step, a fully automated testing station is passed through. This ensures that the machine is fully functional before a reconditioning certificate is issued.

Hygienic cleaning. After the automated functional test is done, the washing machine undergoes a hygienic cleaning process where both the exterior and interior components, particularly the machine drum, which are hygienically relevant, are thoroughly cleaned.

Preparation for shipping. Finally, the refurbished, checked, and cleaned machine is prepared for dispatch and delivered.

Challenges and next steps

With the new business case of the refurbishment of washing machines, Miele faces both technical and economic challenges that arise from the product and the disassembly system.

The high product variability and complexity require high adaptability of the processes and the overall system. Due to the regional limitation of the distribution area of the second-life washing machines, the number of refurbished machines is currently still low compared to the production of new machines. Therefore, most of the de- and reassembly processes can still be carried out manually. Although these manual activities enable the product-specific disassembly processes, they must be automated with increasing quantities in order to ensure scalability and thus, the economic viability of the business case. However, it is precisely this automation capability that must be able to continue the high process adaptability due to the variety of parts and individual inspection results. Adaptive disassembly systems are needed for this purpose, which offer the possibility of scaling the presented business case and thus enabling the industrial expansion. The system adaptivity of the target system can also be increased in this way, because the system can respond variably to different quantities and fluctuating batch sizes. The already familiar assembly system offers potential for automating the disassembly system, since it is possible to use parallels for the first automation steps. The complete automation of the disassembly system then represents a long-term task due to the adaptivity required for the various product states. In addition, there is a need for appropriate planning and control processes for the disassembly. Furthermore, the use of data represents a central enabler of adaptive processes: Sensor technology enables process adaptation of disassembly activities based on the actual condition of the components.

In summary, it can be stated that at Miele the history of traditionally durable products has been perpetuated: Certified refurbishment can additionally enable a “second life” for these appliances, so that their service life is extended beyond their first life cycle. Refurbishment with adaptive disassembly thus contributes to resource cycles in a novel way and can thus even enable tapping into new groups of customers. In addition, leasing models and “Pay-per-use options” can further increase the customer base for refurbished appliances in the future. For the development of larger markets, the automation of the disassembly system while maintaining the current adaptability are key tasks.

4.2 Disassembly of car battery boxes

Starting situation

The Ford Motor Company is a global automotive corporation with 186,000 employees (2020) and a revenue of 136.3 billion USD (2021) [59]. In the global effort to reduce CO_2 emissions, EU member states agreed in the EU Environment Council in 2023 that newly registered vehicles must no longer emit CO_2 from 2035 onwards [60]. In response, Ford of Europe has declared its intention to produce and sell only electric vehicles in Europe starting from 2030 [61]. At the Ford Werke GmbH in Cologne, pure electric vehicles on a VW platform will be produced from 2023 onwards. As per the EU Battery Directive, battery manufacturers are required to have a take-back system and comply with strict collection quotas [62]. Therefore, Ford anticipates several hundred thousand returned batteries annually in the EU within the next 10-15 years. At the end of their use phase, the installed batteries must be recycled, but they also have potential for second-life applications with the current cell technology.

Table 2: Overview Ford Motor Company Use Case

Company:	Ford Motor Company
Product:	Battery of Electric Vehicles
R-Strategy:	Remanufacture, Repurpose, Recycling
Main Challenges:	Return Logistics and Legal Conditions
Most Important Enabler Technology:	Design for Disassembly

Objective of the use case and structure of the product

The goal of an adaptive disassembly system at Ford is to non-destructively disassemble batteries down to the module level in order to return them to the circular economy in various ways. Research projects have already been launched with partners and universities, the results of which can be used to set up pilot plants. The following options for return are currently conceivable:

- The battery is disassembled and reassembled as well as tested to be put on the market as a replacement battery or for used cars (Remanufacturing).
- The battery is used for another purpose (Repurpose).
- The valuable metals of the battery are recovered and used for the production of new batteries (Recycling).

Besides the condition of the batteries, the recovery process depends on the used cell chemistry. Currently, lithium-ion batteries, with cathode materials based on nickel, manganese, and cobalt (NMC) in different compositions, compete with batteries that do not rely on these sometimes expensive and problematic materials in terms of extraction and safety under mechanical and thermal influences. Lithium iron phosphate (LFP) batteries represent such an alternative within the above-mentioned timeframe. This leads to high product variability and complexity for the reprocessing.

As shown in Figure 7, the battery along with its individual battery modules is embedded in a battery box of the vehicle. The control system, cooling system, and wiring are also located there. The modular design of the battery allows for a high level of disassembly depth. In addition to the valuable battery modules, the other components can be used in different paths: The metal plates and battery boxes are expected to be melted down because, first, the design for new vehicles has changed within the vehicle's lifetime and, second, aging due to external influences is significant. The viscosity of aged coolant causes deformation when the plates are disassembled, which precludes reuse at the current level. The wiring, for example, can be returned to the circular economy through the recycling process that already exists today. Increasing the viscosity of aged thermal paste leads to deformation in some battery designs when the plates are disassembled, which precludes reuse. Newer designs have already solved this problem.

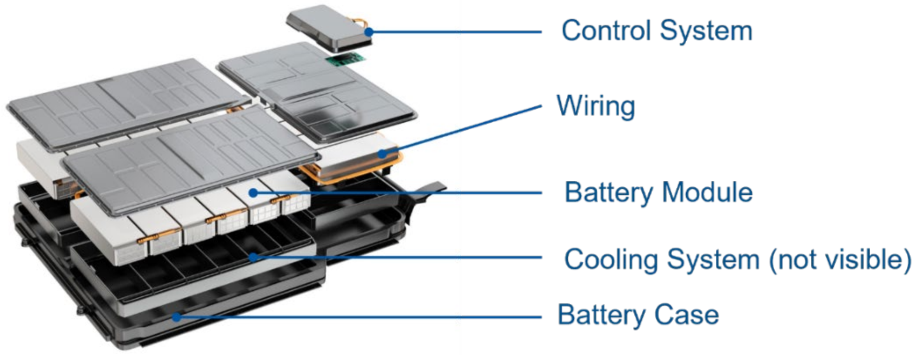

Figure 7: Schematic structure of a battery box (c) iStock

Features of the disassembly system

In the technical design of the disassembly system with regard to the solution components presented in chapter 3, there are various possibilities depending on the requirements, which will be discussed at this point.

The battery box's steel construction provides protection for the valuable battery modules against external influences. Tests done so far suggest that corrosion is unlikely to have a significant effect on the system and internal components are well-maintained during reprocessing. Consequently, less adaptability is required from the system in response to mechanical changes. Automatic mechanized testing is achievable, such as with seams and screws during production. As such, the degree of automation for the disassembly can be similar to that of an assembly process. However, identifying variations will require additional sensory capabilities. If only manufacturer-specific systems are present in the disassembly system, the vehicle IDs can be cross-checked with an internal database and predetermined disassembly instructions can be uploaded. In addition to fully automated disassembly, the robot-assisted disassembly discussed in chapter 3 is also possible, especially for handling heavy components and taking on repetitive tasks, like removing screws or dealing with toxic substances, through human-robot collaboration.

The organizational form also depends on logistical issues. Vehicles must be received decentral. Before the battery box can be completely disassembled in a central factory, it must be removed from the vehicle. This can be done decentral at the acceptance points or centrally within the disassembly system. Since transporting battery boxes without vehicles is more compact but has high safety requirements, the determination is still under discussion. The subsequent disassembly can be set up in modules, unlike assembly in fixed production lines, to be able to react to fluctuating quantities.

Design for disassembly approaches is also of great importance for the design of the disassembly system. The battery is a static component and can therefore be designed to be easily disassembled. However, due to space and design reasons, there is a trend towards integrating the battery into the existing vehicle structure. This leads to higher complexity and product variability. Currently, there are still covers of the battery boxes that are glued, which makes the disassembly more difficult. The integration possibilities into the vehicle structure and the use of screws together with non-adhesive seals instead of adhesives must be evaluated considering a cost calculation for both the assembly and disassembly processes. Non-destructive removal of the battery modules is the necessary boundary condition.

Challenges and next steps

Since small quantities of batteries are initially expected in the next few years (e.g., in the form of batteries with production defects), the industrial design of the disassembly system is still open for discussion. Due to the legal requirements to accept batteries, corresponding logistics (decentralized or centralized) is a priority. One possible approach is to partially incorporate manual disassembly strategies to enable decentralized reprocessing in local workshops. Based on this, the logistics structure for a central disassembly can be set up. In addition, warranty, liability and determination of the value of batteries when repaired battery modules are made available to other companies for second-life applications, as well as the installation of reconditioned battery systems in used vehicles, are issues that have not yet been clarified and could influence the circular economy. For the latter, a uniform (cross-manufacturer) certified procedure should be aimed for, which could also increase customer acceptance of reconditioned batteries.

Developments in cell chemistry have a considerable influence on the possibilities for further use of the batteries. Together with the changes in vehicle design, this means that the disassembly system must evolve continuously. In the disassembly process, occupational safety will play a role due to the materials used, which will further increase the need for automation. If the quantities increase, extensive automation in disassembly lines or within free disassembly modules is necessary. In the automotive industry, assembly systems already have a high degree of maturity, which is why it is possible to fall back on well-known technologies and partners. However, the strong predicted growth will require the expanded use of data and sensors to enable high adaptivity. Sensor technology can be used, as is currently the case in assembly, to position products and machines relative to each other and, most importantly, to accurately determine the condition and residual value of the battery.

4.3 Sneaker remanufacturing

Starting situation

1.1 PCH Innovations is a Berlin-based creative engineering studio that specializes in robotics for circularity, generative AI, and computer vision solutions. Founded in Los Angeles in 2006, the company focuses on developing tailor-made system innovations that can be scaled up to industrial applications. As EU eco-design directives have been extended to include product categories like clothing and footwear, their recent efforts have been directed towards creating systems that can handle deformable materials such as textiles, shoes, backpacks, and tents. Their overarching goal is to reduce the ecological impact of products by minimizing material use and maximizing resource efficiency through appropriate reprocessing and recycling measures. PCH Innovations is currently exploring assorted automation solutions for the textile industry including dismantling systems for products such as shoes, tents, and backpacks, that facilitate recycling and contribute to a more sustainable future.

Table 3: Overview PCH Innovations Use Case

Company:	PCH Innovations
Product:	Shoes
R-Strategy:	Remanufacture, Repair, Recycling
Main Challenges:	Product Variance and Handling
Most Important Enabler Technology:	Sensors + Machine Learning

Aim of the use-case and structure of the product

Although many boundary conditions of dismantling are still unknown, a process can be defined with four central tasks of detection, sorting, handling and disassembly, which must be performed in this or a comparable order:

Recognition. The first task is to both identify the shoes to be dismantled and their condition. Computer vision systems play a major role here but one challenge is the large amount of training data required to be able to recognize all brands, models, and conditions with a high degree of certainty. A digital product file could provide data on the composition of the product by means of an RFID transponder. In addition to the combination of conventional industrial cameras with computer vision, special imaging technologies such as infrared spectroscopy can also be used to determine the materials of the present shoe and to estimate the condition of these materials. Based on this data, further process steps can be planned accordingly and initiated.

Sorting. Depending on the business case and the capabilities of the disassembly system, different types of sorting are possible. A product-side challenge lies in the recognition and sorting by brand, material composition or shoe structure. The manufacturer's own logistics system could significantly reduce the variation in advance with the help of used shoe collection centers that are easily accessible for customers. In addition, sorting must be carried out according to product condition, which decisively determines the type of return. It is possible to differentiate between complete dismantling (recycling or remanufacturing), dismantling components (e.g. repair) or even the omission of dismantling (resell).

Handling. Handling the shoe – a semi-soft, deformable object – poses a key challenge to the reliability and stability of the process, as any automated operation requires counter-pressure from the inside of the shoe. To guarantee the defined positioning of the materials and provide the required uniform back pressure in automated shoe production, lasts are used, i.e., fittings made of high-density plastic that are modeled after human feet. However, as lasts can only be used specifically for individual models and it is not possible to reinsert them into a finished shoe, research is currently being carried out on flexibly expandable lasts. For this purpose, PCH Innovations has developed a one-way expandable last for Nike's *Bot Initiated Longevity Lab system*. A general-purpose strip should be expandable in multiple directions and use potentially smart, programmable, shape-changing materials. A sketch of the possible implementation of the handling in combination with a sensor system for detection is given in Figure 8.

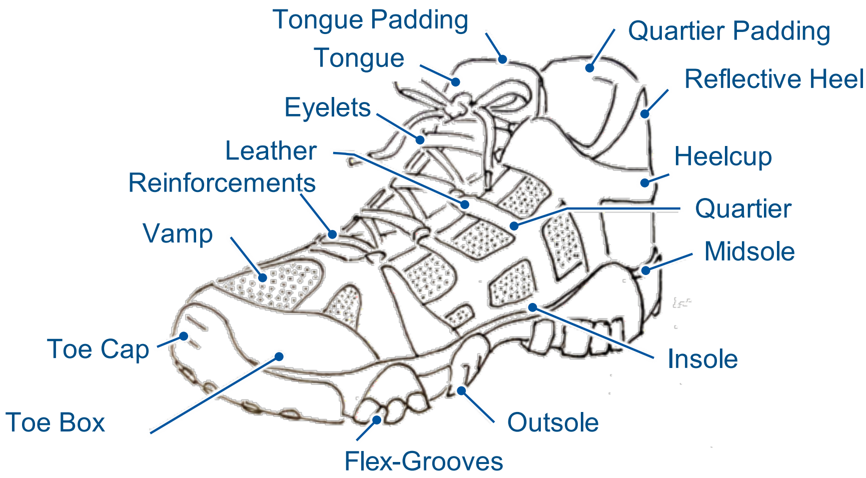

Figure 8: Example of a shoe and its components

Features of the disassembly system

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Disassembly. Finally, to successfully dismantle shoes, additional steps for reconditioning and repair are necessary. During the dismantling process, the use of appropriate tools is essential for removing individual layers of material. Cutting, grinding, vacuuming, as well as heat or chemical separation technologies may be required. The flexible and deformable material layers resulting from this process must be treated individually and sorted into their respective material flows or further disassembly steps. The goal is to minimize the number of tools needed while covering a wide range of materials and technologies. This requires the development of customized end effectors and grippers for robotic systems that can adapt to the varying needs of different types of footwear and materials.

Challenges and next steps

To develop and implement effective industrial reprocessing processes, the highest priority is identifying the wide variety of footwear models and their diverse states. While computer vision systems can detect material properties and variants with increasing accuracy, additional data support is still necessary. However, since shoes typically lack embedded sensors, determining their condition is difficult. One realistic solution is to embed RFID transponders or memory that provide information about materials used and even disassembly instructions to support the planning of disassembly steps. Challenges also arise during dismantling itself, as substances must be decontaminated or cleaned of adhesive residues if all materials are to be returned to their own material streams. Shoe production must already be designed with "Design for Disassembly" approaches for dismantling. Ultimately, the realization of a shoe dismantling system depends on the business case. Without a legal obligation to take-back or clear customer demand, widespread use of dismantling systems for shoes is not yet possible. However, motivating manufacturers to implement dismantling or corresponding recycling quotas can help promote their use.

4.4 Summary of the current status quo from the perspective of companies

The goal of circular economy strategies is to promote ecological and economic objectives in companies for a sustainable production approach. As illustrated in the individual use cases, the potential of the circular economy is recognized and promoted by the industry. New regulatory provisions are important drivers for the development towards a circular economy. Above all, the steadily increasing customer willingness for sustainable products has a strong positive influence on this development. Circular economy also opens up new business perspectives by allowing companies to differentiate themselves within the competition market by offering "second-life" products. Therefore, the implementation speed of industrial reprocessing systems is increasing rapidly, making the design of disassembly and remanufacturing systems a central concern.

Since the presented use cases are currently being implemented, these activities are primarily carried out manually, so individual product states can be treated accordingly. However, disassembly systems enable circular economy to be expanded to industrial scales. In contrast to established assembly systems, the variance of product types and conditions within the disassembly is significantly higher for companies. Therefore, a rigid automation of the system is not sufficient. Rather, for further scaling, disassembly requires process automation with high adaptability, which can be implemented using available data and sensors.

When comparing the use cases with the presented vision of an adaptive disassembly system, differences in terms of the depth of disassembly and the degree of destruction are noticeable. One commonality of the three discussed application cases is the need for high process adaptability. In the case of washing machine refurbishment, process adaptability can be depicted by manual activities. For the disassembly of car batteries, a modular design offers potential to implement process adaptability on an industrial scale. System adaptability is not initially set as a central focus at this early stage, but this feature will be of great importance for the design of disassembly systems in the further development, as product and technology cycles become shorter, and the number of variants increases. While circular economy strategies have become a strategic topic in companies, a variety of challenges remains that need to be solved through appropriate enabling technologies.

5 Conclusion

An efficient use of resources and the expansion of product life cycles represent a central perspective for sustainably oriented companies. The EU's efforts to establish a circular economy motivates companies early on to implement sustainable systems, and also allows new business opportunities. Potentially, industrial-scale reprocessing can be achieved through the implementation of automated disassembly systems. These systems must have adaptive capabilities, as rule-based automation alone cannot account for the wide range of products and conditions.

Based on the motivation (chapter 1) and the basic terminology for the circular economy (chapter 2), this article describes a vision of an adaptive disassembly system and its characteristics to support resource loops (chapter 3). The core of the article focuses on use cases such as the "Refurbishment processes of second-life washing machines," "Disassembly of car battery boxes," and "Remanufacturing of leisure shoes" (chapter 4). Although some aspects are tailored to specific products, commonalities, and challenges in establishing disassembly systems across various products are also discussed.

Furthermore, in order to be able to react to strong fluctuations in reprocessing, high-quality and consistent data is necessary. Product variants and conditions serve as a basis for decision-making. By automating the determination of the product condition, the assessment efficiency could potentially increase: Data recorded from e.g., depth-sensing cameras can train AI models to classify components, and thus resulting in an automated classification of the product condition and its variation from the original product directly from the start.

Additionally, to respond to condition assessments effectively, the actual reprocessing should be adaptive. This requires machines to use their own reasoning to determine their actions, rather than simply following a predefined set of instructions. Advanced sensors like laser scanners and depth-sensing cameras facilitate process monitoring and enable adaptive tool positioning. Using 5G mobile communication standards and edge computing, sensor data processing can be done in central data centers, providing cost-effective access to powerful robotics control and AI algorithms for fleets of robots. By implementing adaptive automated processes, it becomes possible to control condition variance in an industrial setting.

While the listed action areas mainly concern the short- and medium-term goals within the industry, there are also tasks that will require long-term solutions and collaboration with multiple stakeholders:

Concepts of data acquisition and utilization are a long-term significant task. As described, data is already the basis for all actions in adaptive processes. However, in the future, the necessary data should be transmitted with the product itself, eliminating the need for strenuous data collection within condition assessments. For data of the product structure and the used materials the digital product file offers one solution, which is presented in more detail in the article "Re-Manufacturing Green Factory". On the other hand, data from the entire product life cycle - and especially from the use phase - can be monitored to provide information about the product condition. The goal is to make decisions for the reprocessing in combination with predictive algorithms to optimally deal with the variance of the product state.

In addition, it is necessary that the industry, research organizations, and lawmakers work together in order to standardize requirements for reprocessed products so that the market and the quality demands of customers are brought together in a suitable way. Standardization of product components will also make disassembly easier by reducing product type variance right from the beginning. Additionally, legal issues related to the storage and processing of usage data from the product life cycle need to be addressed by governmental institutions. Furthermore, there is a need to define liability issues for reprocessed products.

Necessary fields of action can be summarized as follows:

- Collection of product and usage data throughout the entire product life cycle
- Automated condition assessments
- Adaptive and automated disassembly processes enabled by sensors and AI systems
- Standardization and modularity for "Design for Disassembly"
- Legal framework for data storage from the usage phase.

From an overarching perspective, it is apparent that implementing industrial systems for reprocessing requires not one single solution, but rather several different action areas that must be pursued simultaneously. Just as assembly lines are specialized and work with high precision, but only act economically due to the large quantities, these requirements also apply to disassembly systems. However, these must be able to handle much greater variance within the reprocessing, so adaptivity must be enabled as a central characteristic. The concrete design of resource cycles requires diverse technological, but also strategic components. In this way, adaptive automated disassembly helps to use resources in a variety of product life cycles with additional value creation opportunities.

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1.3 New Modularity and Technology Roadmapping

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Abstract

New Modularity and Technology Roadmapping

By focusing on recycling, lower energy consumption and reduced use of environmentally harmful (raw) materials, sustainability can only be increased to a certain extent and usually requires compensation for the associated costs. In contrast, a change in thinking and a radical transformation of the value creation towards a circular economy offer superior ecological and economic potential. This is realized by an active extension of utilization cycles and the continuous increase of product value through upgrades during the utilization phase, creating the possibility of recurring monetization.

Accordingly, the key to this paradigm shift lies in a new product modularization for the realization of a circular economy and in an extended technology planning to anticipate the required flexibility and upgrades. Therefore, the goal of modularization is no longer the realization of economies of scale but enabling the value-enhancing extension of product lifetimes through module upgrades and replacements. This means that technology planning should no longer focus exclusively on new products, but in particular also on upgrades for existing products. As a consequence, holistic circularity roadmaps are emerging instead of roadmaps for individual products.

Keywords: Circular Economy, Product Modularization, Technology Planning, Green Growth

Kurzfassung

Neue Modularität und Technologie-Roadmapping

Durch einen Fokus auf Recycling, geringere Energieverbräuche und verminderten Einsatz umweltschädlicher Rohstoffe kann die Nachhaltigkeit nur bis zu einem gewissen Grad gesteigert werden und erfordert meist die Kompensierung damit einhergehender Kosten. Ein Umdenken und eine radikale Transformation der Wertschöpfung hin zur Zirkularität bieten demgegenüber ökonomische Potenziale, die den Status-Quo deutlich übersteigen. Der Hebel dafür, ist die aktive Verlängerung von Kreisläufen und die Wertsteigerung durch das *Upgraden* von Produkten während der Nutzungsphase. Dies schafft die Möglichkeit der kontinuierlichen Monetarisierung von Upgrade-Potenzialen, während eine ressourcenausschöpfende Wertsteigerung über die Lebenszyklen eine ganzheitli-che ökologische Nachhaltigkeit erreichbar macht.

Schlüssel zu diesem Paradigmenwechsel liegen in der Produktmodularisierung und Technologieplanung. Zur Realisierung kreislauffähiger Produkte müssen diese verstärkt integriert und synchronisiert werden. Um heute und morgen ökologische und ökonomisch nachhaltige Leistungen anzubieten, ist ein Verständnis über Märkte und Kunden der Cir-cular Economy notwendig. Außerdem erfordern die regelmäßigen Upgrades ein frühzei-tiges Antizipieren relevanter Technologiesprünge. Unter Berücksichtigung dieser beiden Blickrichtungen muss eine Produktarchitektur für kreislauffähige Produkte entwickelt und die Technologiebetrachtung vertikal (um Re-X-Technologien) sowie horizontal (um Remanufacturing und Modul-Upgrades) erweitert werden.

Schlagwörter: Circular Economy, Produktmodularisierung, Technologie-Roadmapping, Green Growth

1 Introduction

1.1 Why efficiency improvements are not sufficient

"Take, Make, Waste" - this so far prevailing production and consumption logic is unmistakably taking our planet to the limits of its carrying capacity. The consumption of natural resources on a global average is 1.75 times higher than the renewable resources provided by our planet and does not cast doubt on the urgent need for action. [1]. Especially a focus at Germany, where the factor of resource overuse of the earth is at a factor of 3 [2], underlines the necessity to fundamentally transform today's linear economy as soon as possible. The response to these worrying effects of linear economies is to increase efficiency and use environmentally friendly substitutes. However, any linear economic system based on the consumption of finite resources – no matter how efficient – entails negative environmental impacts along the entire material chain. To achieve a substantial decoupling of economic activities from resource consumption, a shift in thinking towards a systematic approach that enables value creation without resource consumption is needed. [3]-[6]

1.2 The Circular Economy as a Green North Star

According to the ELLEN MACARTHUR FOUNDATION [7] a *Circular Economy* is a restorative or regenerative industrial system by intent and design. It replaces the "end-of-life" concept with restoration, relies on the use of renewable energy, eliminates the use of harmful chemicals that interfere with reuse, and strives to eliminate waste through superior design of materials, products, systems, and business models. This ideal economic system can be characterized by the following three key points:

1. The realization of products made from recycled and renewable raw materials, produced with renewable resources and with no or minimal environmental impact
2. Optimal product utilization over several life cycles combined with systematic recycling or reuse of products and its components in cycles
3. Creation of ecological and economic added value for customers, for the company itself and the stakeholders concerned.

This Green North Star is characterized by a high ecological and economical benefit, but also by a significant distinction from the current way manufacturing companies act and think.

In order to effectively approach this goal, companies must align their strategy with it, increase sustainability in their existing core businesses and approach the potential of the Circular Economy. Only with great far-sightedness companies are able to invest in the right developments today that will enable them to maximize environmental and eco-benefit potential in the future. Incremental development and extrapolation of development activities alone, based on today's core business, can result in companies having to react unprepared to upcoming fundamental product and technology changes. This increases the risk of being disrupted in the future. Companies can prepare for this by developing their capabilities simultaneously in the following four potential dimensions: modularization, technology, value creation and revenue. By combining these different potentials, companies can succeed in achieving the goal set out in Figure 1 to successfully follow the transformation path to the Green North Star of Circular Economy.

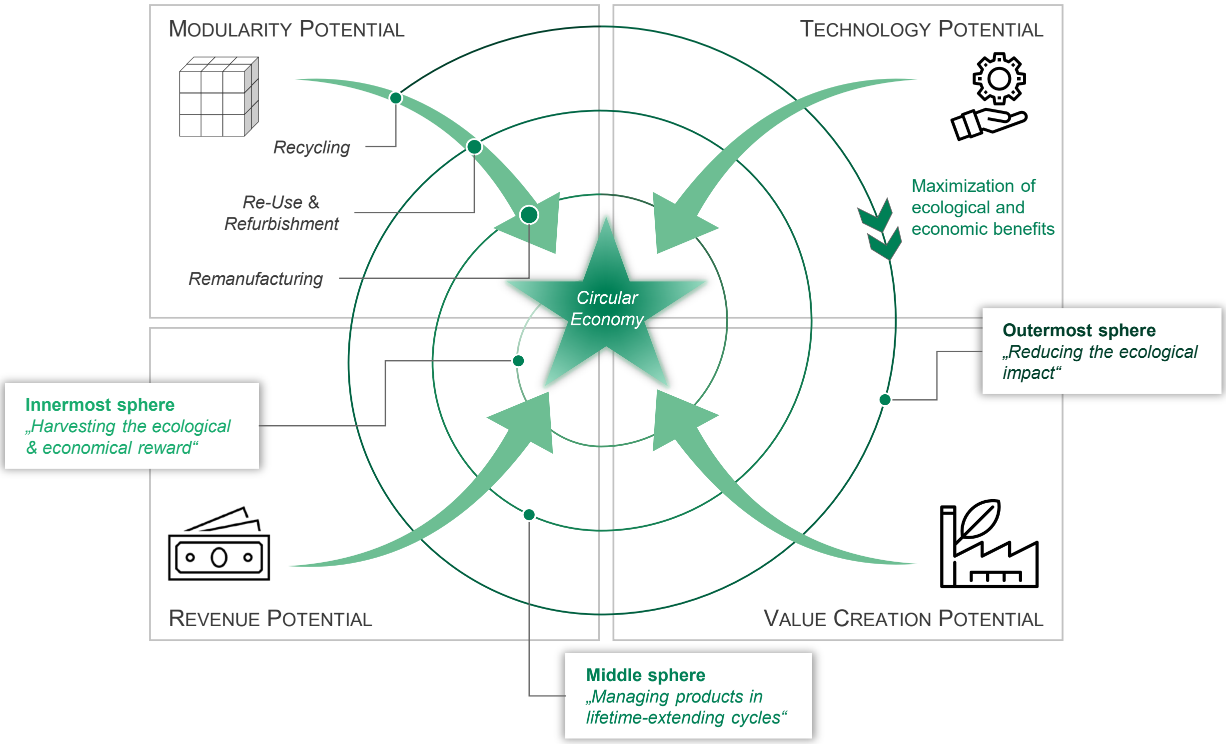

Figure 1: Synchronization of modularity, technology, value creation and revenue potentials for the transformation to a Circular Economy

The potential dimension of modularization describes that modularization contributes to the transformation path to the Circular Economy. While at the beginning of the transformation the focus is on realizing efficiency improvements through a reduction in complexity, a higher modularization will enable the exchange of modules in the future and therefore *refurbishment* and *remanufacturing* of products and modules will become feasible.

The technology potential describes the contribution of existing and future technologies to the transformation process. In this context, potential is initially realized through the optimization of existing technologies, which can lead to efficiency improvements. Along the transformation path, new technologies must be evaluated and developed more frequently to enable and improve the different re-X cycles.

The value creation potential describes the potential that arises through additional value creationwithin a Circular Economy. Additional value includes for example the reprocessing or value enhancement of modules, resulting in new value creation steps.

The revenue potential describes the economic potential created by the transformation. This contributes to the transformation path in an important way but can only be realized if the three other dimensions are developed further alongside. The potential increases along the transformation path from the realization of minor savings and revenue increases to new revenue channels through the monetization of product upgrades and the additional value creation steps described.

The bigger picture shows ecological and economic benefits that can be realized increasingly. However, in order to realize the potential for value creation and earnings, it is necessary to realize the potential for modularization and technology at the same time. A complete corporate transformation is therefore required, wherein ecological and economic benefits are successively aligned on the transformation path and behave as synergetic dimensions towards the Green North Star of the Circular Economy. For a more detailed description of this transformation path, it is divided into three spheres, which are examined in more detail below.

The outermost sphere - "Reducing the ecological impact".

Increasing sustainability in a company's core business represents a necessity. By focusing on *recycling*, lower energy consumption in production and use, and reduced use of environmentally harmful raw materials, ecological sustainability can be increased to a certain extent. Therefore, existing product and production technologies are optimized, and value creation is designed for an efficient resource consumption. However, this increase in ecological sustainability enables only a marginal increase in economic benefits because, apart from possible potential savings through more efficient use of resources or increases in sales through image enhancement, the fundamental actions of the company have not changed.

Many companies, however, are currently sticking to these basic activities and see a further increase in sustainability beyond this point as a major challenge. In this context, the potential benefits in the next spheres increase over proportionately, as completely new business potentials can be explored.

The middle sphere - "Managing products in lifetime-extending cycles".

If companies extend their recycling and efficiency optimization activities through approaches of *re-use* and *refurbishment*, they can extend the lifespan of their products and moreover manage their products (or parts of it) in value-creating re-X cycles. In addition to optimized value creation, value preservation (over an extended period of time) is realized. This offers the opportunity to monetize arbitrage potentials between degrading product lives and thus generate an economic benefit. However, this requires the targeted further development of parts of the core business and the underlying technologies.

However, companies are still not exploiting their full sustainability potential at that point. To do so, companies need to make further efforts in all four potential dimensions and combine them in the sense of the Circular Economy.

The innermost sphere - "Harvesting the ecological & economical rewards".

Only through rethinking and radical transformation of a companies' business activities towards the Circular Economy, it is possible to create the maximum ecological and economic benefit in the innermost sphere. The lever for this is the active and value-enhancing extension of life cycles through industrial *remanufacturing* and the *upgrading* of products during the use phase. Therefore, cycles of products as well as modules and product components have to be considered. In this way, value creation from available resources is maximized and realized over the life cycles and thus greater ecological sustainability is achievable. In addition, the economic potential is increased by the possibility of continuous monetization through upgrades in the respective product and module cycles. However, this requires the development of new technologies both in the areas of product and production and in the new areas that make it possible to enable re-X cycles (e.g., recycling technologies and digital technologies).

By describing the four potential dimensions and the three spheres, the trajectory of the sustainability transformation can be described. This trajectory inevitably heads for the Green North Star of the Circular Economy and intersects the four potential dimensions several times. This defines the focus areas of the circularity activities in the three spheres and potential dimension; these activities are summarized in Figure 2.

	Outermost sphere *„Reducing the ecological impact"*	**Middle sphere** *"Managing products in lifetime-extending cycles"*	**Innermost sphere** *"Harvesting the ecological & economical rewards"*
	Focus on *recycling*, low energy consumption and less harmful raw materials	Extended lifetime through *re-use* and *refurbishment*	Extended re-X cycles through *remanufacturing*
MODULARITY POTENTIAL	Resource conservation and increased efficiency through complexity reduction	Module replacement within the life cycles to extend the life time	Value enhancement during extended life cycles at product and module level
TECHNOLOGY POTENTIAL	Optimization of existing technologies	Enhancement of technologies	Resource exploiting value enhancement
VALUE CREATION POTENTIAL	Resource-efficient value creation	Resource optimized value creation & capture	Resource exploiting value enhancement
REVENUE POTENTIAL	Limited opportunities for savings and revenue growth	Discrete monetization of arbitrage potentials between degrading product lives	Continuous monetization of upgrade potential in product cycles

Figure 2: The characteristics of the trajectory towards Circular Economy

The current challenge for companies is to focus not only on the initial circularity activities but on their holistic transformation efforts. Companies are currently still neglecting the fact that they need to look ahead when it comes to investing. They need to invest today in activities that are required on the further path to the Circular Economy in order to prevent their business from being disrupted in the future. Companies need to understand their holistic sustainability potentials based on the target image of the Green North Star and build their strategic program aligned to the four potential dimensions in a synergetic manner. This is the only way that development opportunities can be realized in a balanced way without neglecting current performance.

Practical example: Webasto SE

Playground Green Mechanism - creative set-up for sustainable product solutions

Webasto is one of the 100 largest suppliers to the automotive industry and specialized in the development and manufacturing of roof and thermal systems as well as battery and charging solutions for electromobility.

Looking at ambitious climate targets, Webasto is already working on how future generations of their products can become more sustainable. The "Playground Green Mechanism" project offers development teams an unrestricted environment, in which they can develop under their own premises, detached from all requirements. Their target is to ensure the functionality of the product while reducing energy consumption by 50 percent over the entire life cycle and create a so-called "Minimum Viable Sustainable Product"

(MVSP). The initial results of this less restrictive environment testify to enthusiasm and high creativity in the teams at a completely new level.

Webasto's experience shows that breaking down restrictions and requirements promotes the creativity of development teams. For example, ignoring peak requirements like the requirement for their modular roof system architecture to be able to close while driving at 320 km/h and additional headwind, lead to more sustainable products at marginally reduced functionality.

With the help of this project, Webasto is already working towards the Green North Star. Even if the MVSP still costs more than the existing product and is therefore not yet economically viable, the tipping point will come when rising energy prices ensure that the more energy-efficient version becomes more economical, which will ultimately allow ecological and economic potential to be realized.

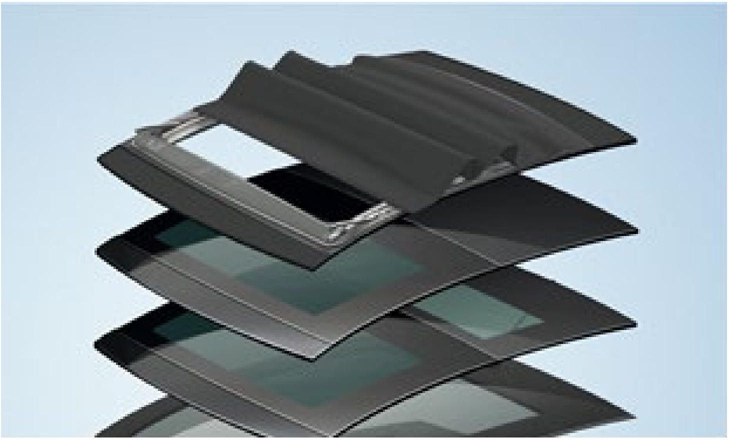

Figure 3: Development of roof systems according to the MVSP approach at Webasto.

1.3 Paradigm shift of product modularization and technology planning

At this point, the question arises what measures can be taken to prepare the company and its products for a Circular Economy. In order to deal with the necessary activities of the innermost sphere, it is necessary to prepare the product architectures of the products for the Circular Economy already today. The product architecture must be designed in a way that individual parts of a product can be exchanged, refurbished or upgraded. Therefore, it is important to provide flexibility in the right places and to implement this through suitable interfaces. Accordingly, the key to the required transformation lies in product modularization for the realization of circular product architectures and technology planning for the anticipation of the required flexibility and upgrades.

By definition, modularization describes the suitable structure of a product by reducing the dependencies between elements (modules) or reducing the interface variants [8]. Accordingly, the aim is to provide standardized interfaces between modules so that a wide variety of module variants can be combined with each other, and a large number of different product variants can be realized for the customer while at the same time achieving a high level of module reuse. The modules have no or only minimal dependencies to each other to ensure that changes to one module do not affect other modules.

But while product modularization in the past focused on realizing economies of scale, for future products it serves as the key enabler for realizing the Circular Economy.

Consequently, modularization faces a paradigm shift that can be described by the trajectory described above from today's linear economy to the Circular Cconomy. In particular, the objective (1.), the way of creating customer value (2.) and the complexity of the requirements for modularization (3.) will change.

	Today's linear economy	Circular Economy
PRODUCT MODULARIZATION	➢ Realization of economies of scale ➢ "Right-sizing" of modules for service provision ➢ Economic criteria for modularization	➢ Regular product upcycling ➢ Service provision only through sustainable modules ➢ Profitability and sustainability as equal criteria
TECHNOLOGY PLANNING	➢ Primarily for new products ➢ Upstream and downstream phases ➢ Separate roadmaps for different products	➢ Primarily for upgrades in existing products ➢ Circularity ecosystem ➢ Circularity roadmaps

Figure 4: Paradigm shift of product modularization and technology planning

1. The change in the objective of modularization begins with the addition of target dimensions. Initially, the focus is on realizing economies of scale, with the aim of reusing as many parts as possible in the product portfolio. Modular products make it possible to reduce complexity in the company, simplify order processing (e.g. through configurators) and standardize production processes. These effects primarily aim at increasing efficiency and thus also offer ecological potential - however, they must not lead to a perceived economically viable overproduction [9]. An increasingly important target dimension of modularization is the extension of product life cycles. This can be achieved by classifying modules according to their expected, value-adding lifespan and by designing modules whose added value has a shorter lifespan than the product itself (e.g., wear parts or components with a high frequency of technical innovations) in a way that allows easy and low-cost replacement during the products life cycle. Furthermore, modularization will enable the "upcycling" of products on a regular basis, i.e., to increase the value of the product by renewing modules. The replaced "old" modules can then be reused in products in lower price segments through "reuse" approaches or are "upcycled" through remanufacturing and can be used in comparable products again.
2. The perception of the customer benefits of modular products will also evolve. A product is purchased because customers expect value and benefit from the features and functions [10]. This often involves solving a customer problem and fulfilling the corresponding needs. The benefit for customers initially arises from the fact that the products can provide the required features and functions as cost-effectively as possible. If the offered products match the customer's needs as closely as possible, this creates an opportunity to increase resource efficiency by not oversizing products and improving their degree of utilization and capacity utilization. In the transition to the Circular Economy, simply "right-sizing" of products is no longer

sufficient and resource-efficient performance is becoming increasingly important. The right measure in this context is to increase the performance of the product without requiring additional resources. This can be achieved by using software adaptations or additional services to enhance product performance. The implication for modularization is the increasing relevance of software and services, which must be considered in future product architectures. At the core of the Circular Economy, the value of a product is no longer measured only in terms of cost, productivity, or performance specifications, but rather as a combination of other sustainability-oriented factors. These factors measure the impact of the product on its environment in terms of ESG (Ecological, Social, Governance) factors and are included in the evaluation of the product's value. Accordingly, the modules of the product must be designed to address these factors as effectively as possible at their initial development. In addition, the development of modules must consider possible second, third and following cycles in the Circular Economy, as well as the possibility of refurbishment, remanufacturing or further re-X strategies.

3. Against the background of the changes already outlined, dividing the product into modules will become a much more complex task than it is today, as further degrees of freedom and target variables have to be considered. Today, modularization is carried out based on an optimization of the variety of module variants, whereby the goal is to divide the product into modules in a way that complex and expensive modules require as few variants as possible in order to be able to serve the entire product portfolio, while the diversification of the product is achieved through simpler and more cost-effective modules. The focus is always on meeting individual customer requirements while simultaneously standardizing product components to realize economies of scale in production and downstream processes. In the context of the Circular Economy, further dimensions must be considered in determining modules and module interfaces. For example, it makes sense to group components with similar life expectancy into a module, since the life of an entire module depends on the life of the shortest-lived component. Another perspective would be the material view from which it is important to be able to recycle the modules at the end of their life cycles. Defining the modules in a way that they support refurbishment or remanufacturing through easy disassembly, reprocessing and upgradeability must be another objective for the modular product architectures of future products. These examples already demonstrate how many perspectives there will be on modularization in the Circular Economy and thus contribute to the increase in complexity. To address this complexity, new methods and tools must be developed to assist in product architecture development for modular and circular products.

The basis of the realization of this change in product modularization is the consideration of appropriate decisions regarding future technological direction and the anticipation and operationalization of future technologies.

The main task of technology planning will be to answer the questions, which technologies and methods will best meet customer requirements, strengthen ecological and economic potential of the company, achieve competitive and time advantages, and expand strengths or reduce weakness. [11].

This is accompanied by a transformation in the orientation of technology planning towards the development of the Circular Economy. This paradigm shift consists of three main aspects: 1. the times in the product life cycle for which the use of technology must be anticipated, 2. the scope of the product life cycles which is taken into account in the planning, and 3. the interdependence between various roadmaps.

1. In their technological orientation, manufacturing companies mainly focus on their future. This results from the current business models of manufacturing companies, which revolve around the one-time transaction of a manufactured product. However, when product life cycles are extended through refurbishment and reuse, companies must adapt their technological decisions accordingly. As the product lifespan will increase and modular design allows the replacement of modules and components, the integration of technologies into existing products will play a key role. Future technologies will then no longer only affect products to be manufactured in the future. In the Circular Economy, regular product upgrades will lead to a new value creation, in which a large part of the value creation will take place in future products after their initial creation. New production, which is the current standard, will decrease proportionately and accordingly, technology planning will primarily focus on existing products.
2. Companies are currently focusing on the technologies they use for (resource-conserving) value creation as well as technologies in upstream or downstream value creation stages due to possible (in)direct dependencies. With the emerge of closed product loops and finally intersecting loops in the transformation to the Circular Economy, this is developing into a systemic technology view in ecosystems, taking into account the interfaces to tangential or overlapping cycles. This increases the scope of planning to include additional relevant technology levels, and technology decisions must not only be positive for the company itself to increase competitiveness but also enforceable in the overall system and therefore positive for all stakeholders.
3. The last paradigm shift in technology planning addresses the transition from classic technology roadmaps for individual products or product families to circularity roadmaps. While technology deployments in products are today still displayed deterministically, in the future roadmaps will consider potential cascading product lifecycles and depict conditions and effects of cascading in terms of the technologies to be deployed. This will eventually lead to the drawing of technology deployment roadmaps, considering possible development scenarios, which map the technology deployment in various products and modules over several life cycles.

In order to realize circular products, product modularization and technology planning must therefore be increasingly integrated. Through iterative synchronization between the product and technology levels, ecologically and economically effective coordination of the life cycles of different module generations across diverse products and stakeholders in overlapping cycles can be enabled.

Practical example: Endress+Hauser AG

Endress+Hauser AG is a leading global supplier of measuring instruments, services and solutions for industrial process engineering.
Their customers work in a wide range of industries, such as chemicals, food, oil and gas, water and wastewater, energy and power plants, metals and mining, and life sciences, characterized by plants with high complexity, harsh conditions and long lifespan of often up to 50 years.

During their long lifespan, these systems are subject to constant internal change. The complexity of these systems increases exponentially due to the required replacement of subsystems, (software) updates and upgrades of components, and the addition of further data recording and data processing systems. Circular Economy leads to a further increase in this complexity with increasingly closed and interdependent cycles of products and components in these systems.

Endress+Hauser therefore recognized early that they had to think of the application areas of its solutions as "systems-of-systems" in order to remain ecologically and economically competitive in the long term. To account for the uncertainties of technology development, user behavior and the solutions of other suppliers, their solutions are designed as robust and resilient subsystems. This results in two specific requirements for product architecture: firstly, each of its solutions, as a component of an overall system, must be designed as a functionally self-contained subsystem, and secondly, the interfaces to other systems must be standardized, physically and software-wise robust, and designed to be compatible over the long term. The latter requires, for example, as a technology, a high degree of automated testing in development to ensure quality in the face of ever-increasing combination diversity. This circumstance was recognized early on and considered accordingly in technology planning.

How this is manifested in their solutions is particularly evident in the example of the well-established Memosens sensor technology, or now Memosens 2.0: Digital sensors with Memosens technology store calibration, sensor and process data directly in the sensor. This allows them to be calibrated and regenerated under optimum conditions in the laboratory. Through regular replacement, refurbishment and calibration, Memosens sensors can live up to 30% longer - even under the harsh application conditions of the process industry. The bayonet lock and automatic sensor recognition enable a "plug & play" replacement of pre-calibrated sensors in the field in the shortest possible time. This reduces the time needed for maintenance and therefore reduces plant downtime costs. Memosens 2.0 sensors can also be integrated into Endress+Hauser's IIoT ecosystem Netilion. There, the sensor and diagnostic data can be evaluated using various applications allowing for precise predictions about the conditions of the sensors and any maintenance needs in addition to information for process optimization. Meanwhile, the new Memosens generation is fully backward compatible, so plant operators are not forced to replace existing measurement lines with new ones: New sensors with an increased range of functions can be used with previously installed transmitters of the older generation without any restrictions. The compatibility of the components also allows for easy extensions and configuration changes at any time preserving past investments.

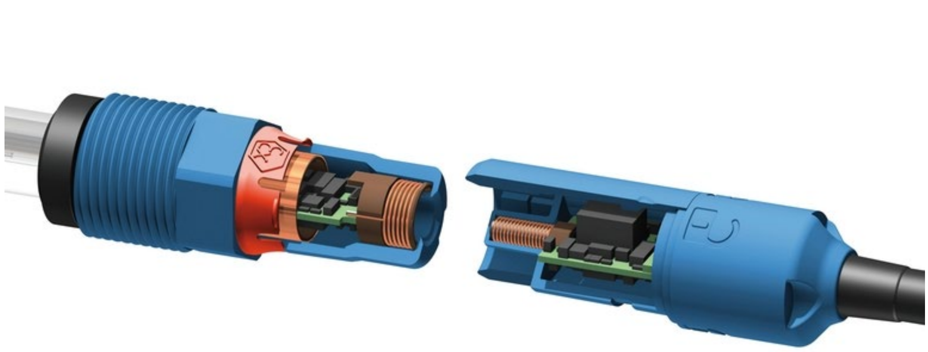

Figure 5: Example of Memosens 2.0 sensor technology from Endress+Hauser

2 Realization of circular products

For the development of modular and circular products, there are four steps that are needed to realize the paradigm shift in product modularization and technology planning along the three phases of analysis, evaluation and realization. In order to offer ecologically and economically sustainable products, it is necessary to understand the changes a transformation to a Circular Economy will bring in markets and among customers. In addition, regular upgrading of products requires the anticipation of relevant technological leaps. Taking these two perspectives into account, it is essential to develop a product architecture for circular products that considers new objectives and degrees of freedom. Additionally, the realization of circular products requires the vertical and horizontal expansion of the technology view. Figure 6 illustrates the three phases and four design tasks for developing modular circular products.

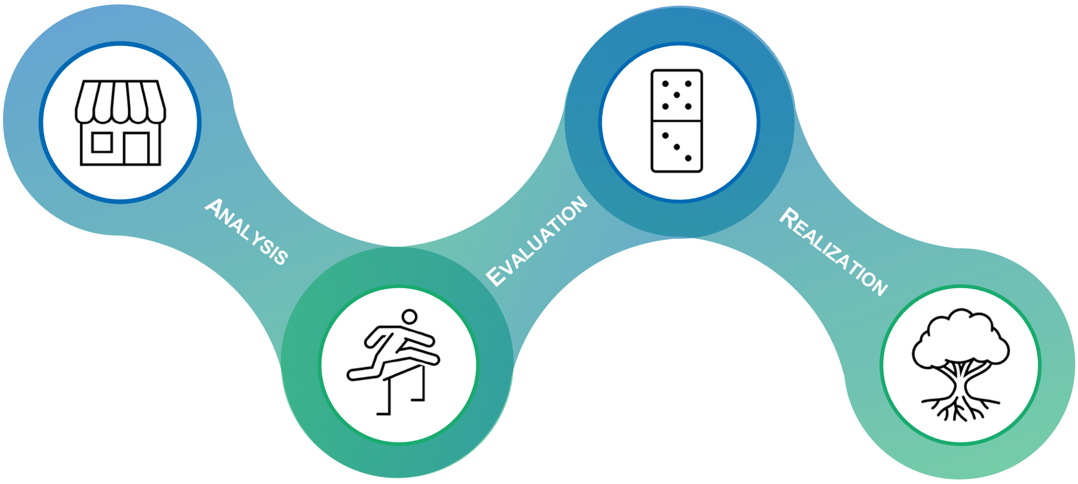

Figure 6: Approach for the development of circular products

2.1 Understand markets and customers in a Circular Economy

First, a deeper understanding of markets and customers in the Circular Economy is the foundation for a successful modular and circular product. On the one hand, it becomes more important to analyze changes in customer needs over time and, on the other hand, to identify potential market segments for re-X products. The consideration of raw materials markets in the context of the Circular Economy also plays a central role. The availability and prices of raw materials or semi-finished products will have an increasingly large influence on the profitability of re-X modules or products.

Practical example: Webasto SE - Market for glass as a semi-finished product

In the production of roof systems for the automotive industry, Webasto requires glass as a semi-finished product. Glass has the advantage that it can be reused as often as desired. Additionally, the recycling of glass has the advantage that it has a lower melting point than its raw materials and thus recycled glass can theoretically be produced with *lower energy consumption. However, the availability of recycled glass is not sufficient to meet global glass demand. This is primarily due to the long lifespan of glass in applications such as building construction, resulting in insufficient glass being returned for recycling.*

In Germany, 7.78 million tons of glass were produced in 2021 [12], of which about 7.6% (i.e., 590,000 tons) were used for the automotive industry [13]. In contrast, only about 14,300 tons of glass were available for recovery from end-of-life vehicles, of which only about 998 tons were ultimately recovered [14].

This example shows that even with the technological prerequisites in place, availability is another important criterion and knowledge of the relevant raw material and semi-finished product markets is of high relevance.

In addition to the raw material and semi-finished product markets, the sales markets and consequently the customers play an important role, as well. Existing methods need to be adapted to place greater emphasis on long-term forecasts and should be applied iteratively. By means of market segmentation with market segments of homogeneous customer needs, it can be analyzed how customer needs within these segments might change over time. Different methods are suitable for this purpose for different time frames:

1. Current needs *(e.g. conjoint analyses, sales figure analyses, ...)*
2. Short-term forecasts of needs *(e.g. data extrapolation, trend radars, ...)*
3. Long-term forecasts of needs *(e.g. scenario technique, simulations, ...)*

Market and customer analyses strive to identify the potential for re-X products or products with re-X modules. This supports anticipating the reuse of products and modules in the second, third or following life cycle.

Accordingly, within the Circular Economy, a large amount of information must be collected and structured when analyzing markets and customers. Only when all individual pieces of information are interconnected and contextualized a reliable overall picture of possible future scenarios emerge. To support the handling of this abundance of information and its connection, the development of market intelligence is helpful [15].

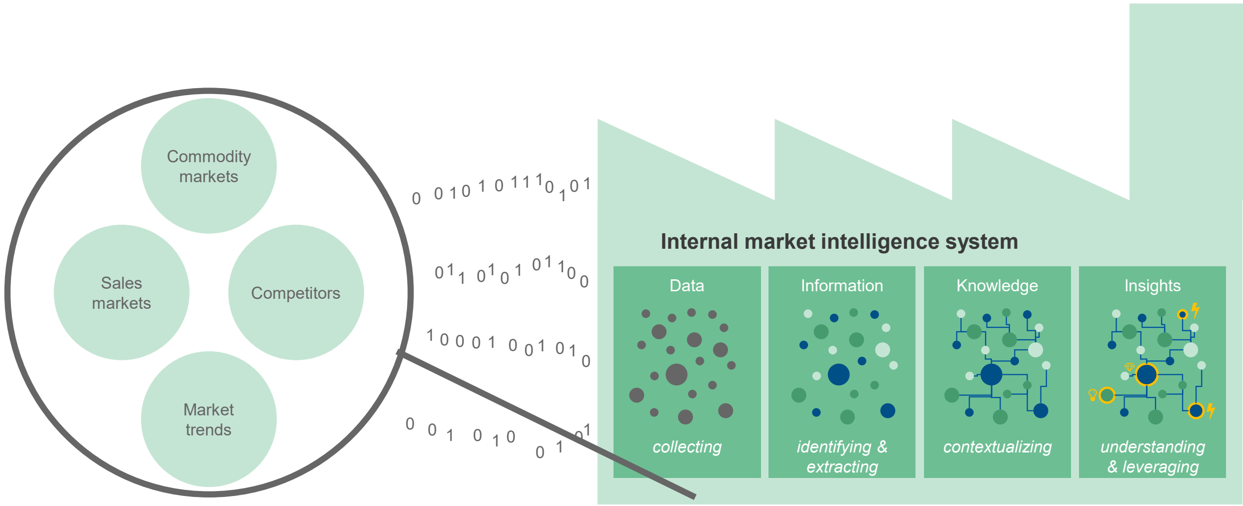

Figure 7: Market intelligence for recording and evaluating market information

2.2 Anticipate technological leaps in the Circular Economy

To realize longer life cycles and the value enhancement within the use phase of products in the Circular Economy, it must be ensured that new functionalities and their underlying technologies can be incorporated into the product both after initial production and during or between use cycles.

This requires anticipating relevant technology leaps. Therefore, it is necessary to ensure upward compatibility of the corresponding modules in product modularization.

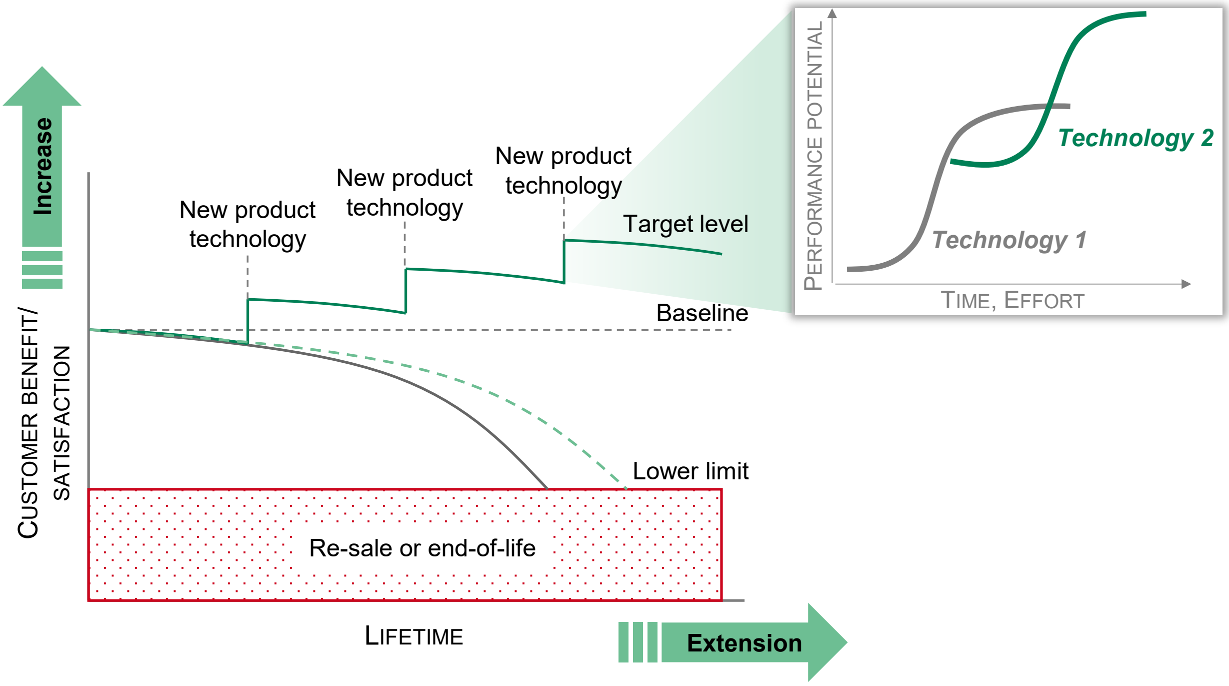

Figure 8: Value enhancement during the useful life through the incorporation of new product technologies

Due to the highly interconnected nature of a circular value creation network, successful anticipation of technology leaps in the Circular Economy is only possible, if there is a holistic view of the system effects of the potential technology leap. The metric that provides insight into the occurrence and extent of a technology leap is the disruption potential. This summarizes the probability of occurrence, speed of occurrence and impact magnitude and can be determined for a circularity ecosystem by means of a system impact analysis. In the context of this system impact analysis, the effects of the potential technology leap are examined along three dimensions: stakeholders in the circularity ecosystem, product lifecycle for technology deployment, and influencing factors that affect the emergence, development or speed of occurrence of a technology leap.

The relevant stakeholders are all actors who are involved in the implementation of the technology leap, apply it or are influenced by it in their actions. Thus, users, manufacturers (including competitors), recyclers, suppliers and complementors generally represent the relevant stakeholders in the value creation network. The government, capital providers and the public are considered under the "influencing factors" dimension due to their non-direct value-influencing role. As the second dimension, the corresponding phases in the product life cycle, or in the successive life cycles are listed for each identified stakeholder in the circular ecosystem.

To examine whether, at what speed and to what extent, a technological leap is likely to prevail, additional factors must be considered that can influence the emergence and establishment of a technological leap across the various phases of the product life cycle and stakeholders in the value network. In addition to political and legal factors, macroeconomic, microeconomic (cost-benefit ratio at the respective stakeholder level), socioeconomic and technological factors must be taken into account, as well. A positive effect indicates a positive impact on a technological leap and can be understood as a main driver. Conversely, a negative impact represents a potential obstacle.

The target picture of the system impact analysis represents a so-called *disruption heat map* (see Figure 9). This provides the possibility of measuring the system maturity of the technology leap, identifying critical entry barriers and anticipating the changes in value creation. This combined analysis enables an assessment of the disruption potential of the technological leap.

The probability of occurrence is shown in the heat map by means of the color-coded impact values for the various stakeholders across the different product life cycles. The probability of occurrence is highest when the impact values are classified as high in all product lifecycle phases and are synchronized across the different stakeholders - this can also be referred to as a high maturity level of the circular ecosystem. A high level of maturity indicates a high readiness and ability to realize and establish a technological leap in the system. In this case, the probability is high that the new technology will become dominant and displace the established technology.

The speed of occurrence results from the interplay of barriers to the establishment of the new technology and the remaining potential of the current technology in place. The remaining potential of the current technology counteracts the disruption potential of a technology leap, so the relative potential advantage is decisive for occurrence. The determined maturity level of the systemic context helps to determine the speed of occurrence of a technology leap, as it provides information regarding existing barriers to the establishment of a technological leap.

The impact magnitude refers to the expected changes in the value creation network when the technological leap occurs. These changes can occur, for example, at the vertical or horizontal level, by shifting or adding phases in the product lifecycle or stakeholders dropping out of or joining the system in future due to changing value creation activities.

Finally, a qualitative-quantitative benefit assessment is required from the perspective of each affected company. A technological leap can affect the company or the company-specific environment on numerous levels and in many ways. Therefore, an analysis of the strategic fit, i.e., the strategic adaptability of a company to opportunities in the external environment, and an assessment of the financial benefit are required. Only then it is possible to determine whether the company is capable to support the technological leap and generate economic value from it. A structured system impact analysis thus enables stakeholders to anticipate relevant technological leaps for upgrading and upcycling products in the Circular Economy at an early stage.

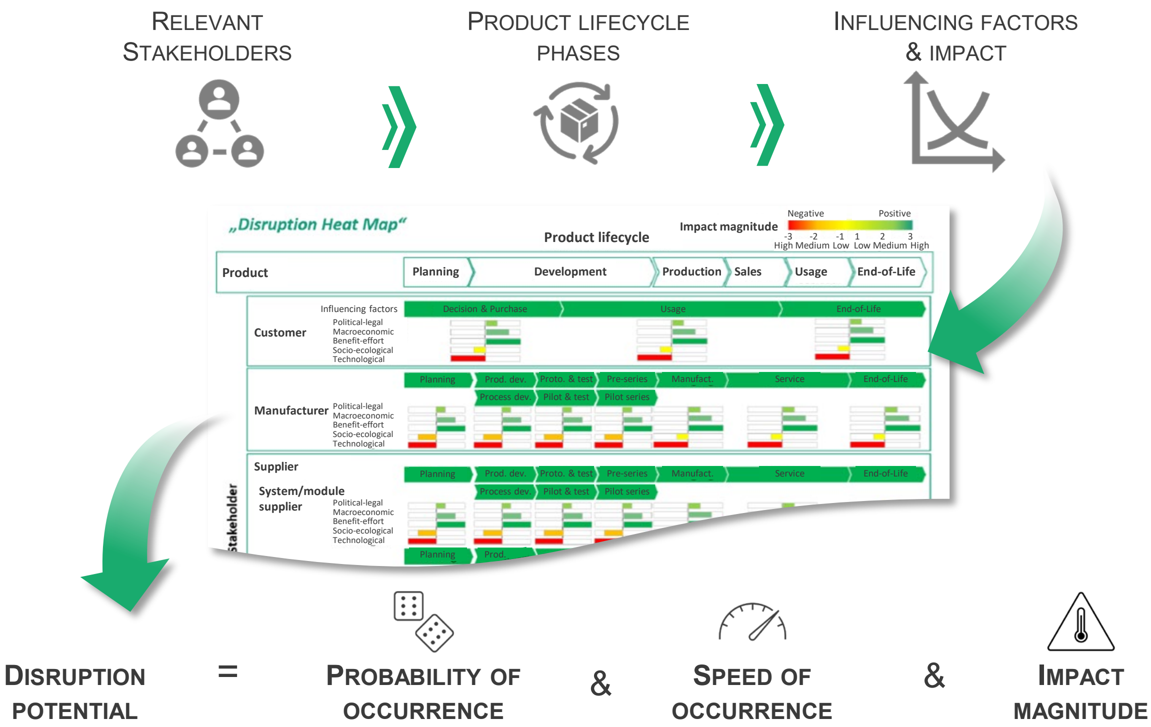

Figure 9: System impact analysis (heat map) to determine the disruption potential of a technological leap

2.3 Design product architectures for circular products

Building on the previous steps, a product architecture for circular products can be developed. It has already been noted that modularization will become a much more complex task in the course of the Circular Economy. This is caused by the expanded target dimensions in terms of lifespan extension and re-X capability, as well as by extended degrees of freedom in the form of possible performance provided by software and services. Due to the multitude of interdependencies and possible influencing parameters, modularization is becoming increasingly complex, making it impossible for development teams to fully grasp the effects of decisions using conventional methods. Therefore, modularization has to be supported by appropriate methods and tools and it evolves into a comprehensive optimization problem. In addition to technical restrictions and interfaces, other specific perspectives of the Circular Economy must be considered to obtain a suitable product architecture. Given the multitude of possible solution alternatives, a system model known from Model-Based Systems Engineering is suitable as a basis for architecture development. The model is based on the well-known RFLP logic (Requirements, Functions, Logic, Product). [16]. Based on the input from step 1, the requirements for the product are initially modelled and the corresponding required functions of the product are derived and linked to the requirements in the system model. The next step involves linking the functions with product elements that are suitable to implement this function. The product elements can be components, assemblies or even software applications. Product functions can often be realized in various ways, which is why different alternatives of product elements come into consideration for realizing the functions. For a complete overall architecture design these alternative technical solutions should be considered and integrated into the system model as alternatives. In the last step of building the system model, attributes (e.g. material, expected lifetime, costs, ...) are assigned to the different product elements and the technical dependencies on other product elements are recorded.

On this basis, relevant perspectives for modular product design in the Circular Economy are defined. Traditionally, modularization is thought of in terms of departments or functional units. The function-oriented perspective will continue to be considered, but further perspectives arise regarding the targeted re-X strategy, lifespan or materials. The re-X strategy considers which strategic goals are pursued with the components in the context of the Circular Economy. In addition, technical restrictions must still be considered to obtain technically feasible modules. Furthermore, the lifespan of the components plays an important role for modularization, where components with a similar lifespan may be combined in a module and exchanged as a bundle. Further perspectives can arise from company-specific requirements.

After all the necessary perspectives have been formulated, they are detailed in criteria. For each individual criterion, the various product elements are evaluated on the underlying attributes. When defining the criteria, the basic idea is that product elements which fulfil the same criteria should be combined in a common module. This can be illustrated using the example of the lifespan perspective: Possible criteria could include "wear resistance", "expected service life" or "frequency of technological innovations". Product elements which are equally evaluated by these criteria should be combined in a common module from the perspective of lifespan. It can be assumed that these product elements will reach a similar lifespan and therefore, when the associated module is replaced, only product elements that are already approaching the end of their lifespan will be replaced, as well. This can prevent a module consisting of fully functional components from being replaced due to a single component.

Finally, the different perspectives must be considered together so that the most synergetic modules possible are created from a holistic perspective. An optimization algorithm determines which alternatives of product elements should be located in a common module. At this point, obligations or prohibitions for module composition are also given as an input into the algorithm. The result is a proposal for the modularization of the product considering the different perspectives as well as possible alternative realizations of product functions.

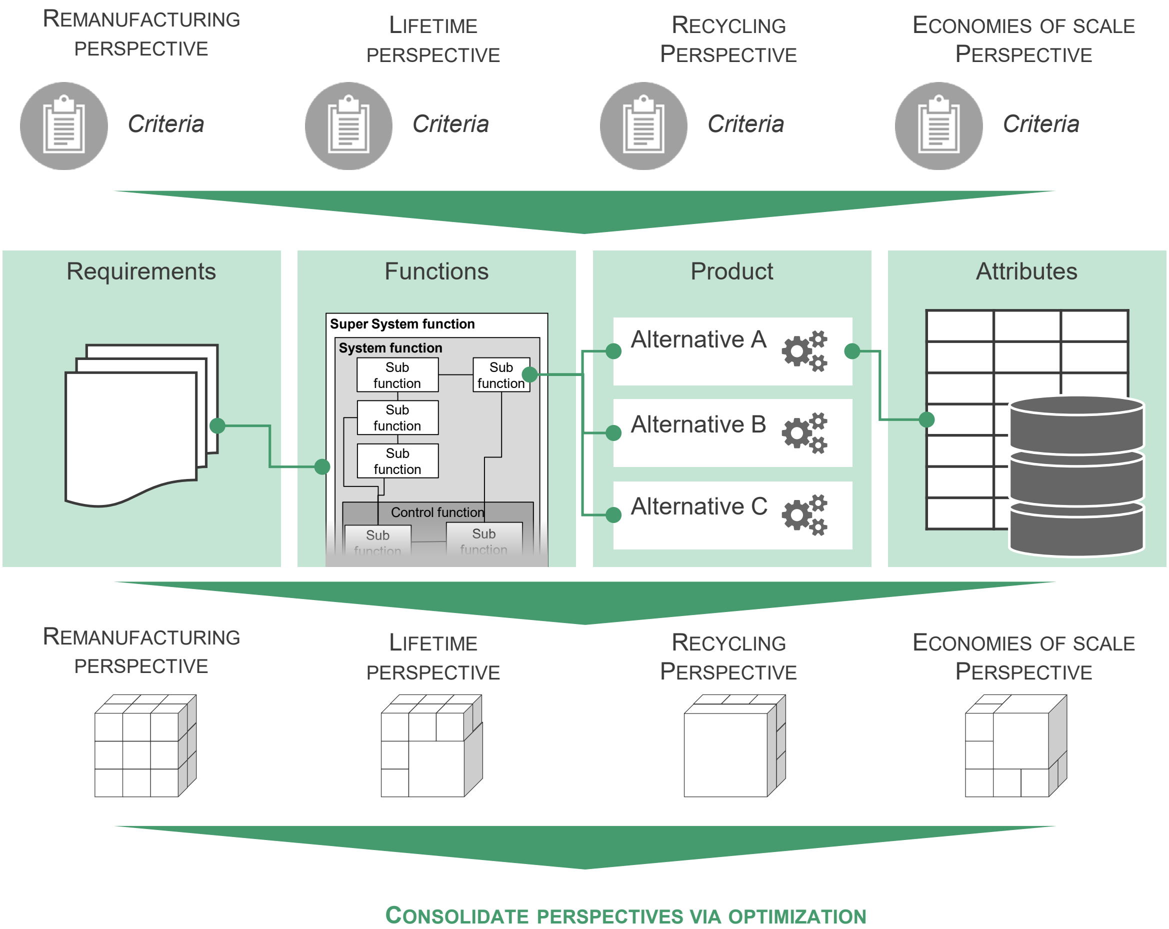

Figure 10: Concept for modularization in the Circular Economy

Practical example: Vaillant GmbH

The Vaillant Group is an internationally family-owned company in the field of heating, ventilation and air-conditioning technology.

At Vaillant Group, development goals for the system architecture are developed in interdisciplinary teams and defined in the form of use cases. Aspects of the Circular Economy are also integrated. In addition to an understanding of the market and customers, future scenarios, long-term forecasts and technological developments form the basis. Finally, the architecture development, which is completely function-oriented and model-based, is approached based on these use cases. The Vaillant system model comprises the requirements, functional and technical levels. The use cases are the decisive input for the requirements level, from which the functions are subsequently derived. The functions form the core of the system architecture and enable a flexible exchange and combination of elements in the technology level. In realizing this flexibility, interface compatibility and standardization is a core factor.

Another aspect of the change in architectural development is the increasing shift of the system boundary of architectures. For example, the system model is no longer limited to the heat generators such as a heat pump itself but encompasses the entire heating system of a building.

Through function-oriented system architecture and the extension of the system boundary, the Vaillant Group is able to carry out the functional upgrades as described above through module expansions and/or replacements. In an overall heating system, for example, the heating pipes can be used for the same length of time as the heating system itself, while radiators, storage tanks or heat pumps can be upgraded in the course of new technical innovations.

Figure 11: The Vaillant Group heat pump is part of the overall heating system and can be replaced or updated on a modular basis as a result of future technological innovations

2.4 Expand technology roadmaps vertically and horizontally

The transformation from linear to circular value creation requires companies to expand their technology planning in two dimensions. Accordingly, a vertically and horizontally expanded technology tree forms the basis for companies to create holistic and integrated roadmaps for realizing circular products.

On the one hand, technology planning in the Circular Economy is no longer solely focused on the products to be manufactured in the future. Rather, in the context of closed loops, companies will repeatedly come into contact with their products or modules of these prod-ucts within a life cycle and need to align their technologies accordingly to this new value creation logic. This requires not only technology planning for new products, but also for revised and functionally updated or "upgraded" products (e.g., through the replacement of modules or software updates).

Moreover, due to the higher interdependencies between the different actors in the Circular Economy, companies no longer have to deal only with product and production technologies that underlie their own value creation. In the Circular Economy, it is necessary to address the process technologies that enable the closing of loops, especially recycling, refurbishment and remanufacturing technologies. This does not mean that companies are not going to close all loops themselves and therefore do not need to master all technolo-gies themselves. Nevertheless, it is necessary that the technology use is orchestrated in the overall system and therefore planned. This is because in circular ecosystems, all technologies and processes are interconnected, and cycles can only be implemented, if all the technologies required can be used in the system in a way that is both economically and ecologically viable.

To visually establish the extended technology consideration in the technology tree as well, it can be extended in two directions as shown in Figure 12. The technology tree enables the identification and structuring of relevant technological resources and capabilities and the representation of both the relationships between the central technologies and their links to the application through functions, modules, products and ultimately markets [11]. The horizontal extension includes the expansion of applications to include products that are intended to be refurbished or regain higher-value state with the help of remanufacturing technologies. Furthermore, the vertical extension offers the possibility to include not only technologies for manufacturing but also technologies for closing the loops (re-X technologies) and thus actively plan their usage.

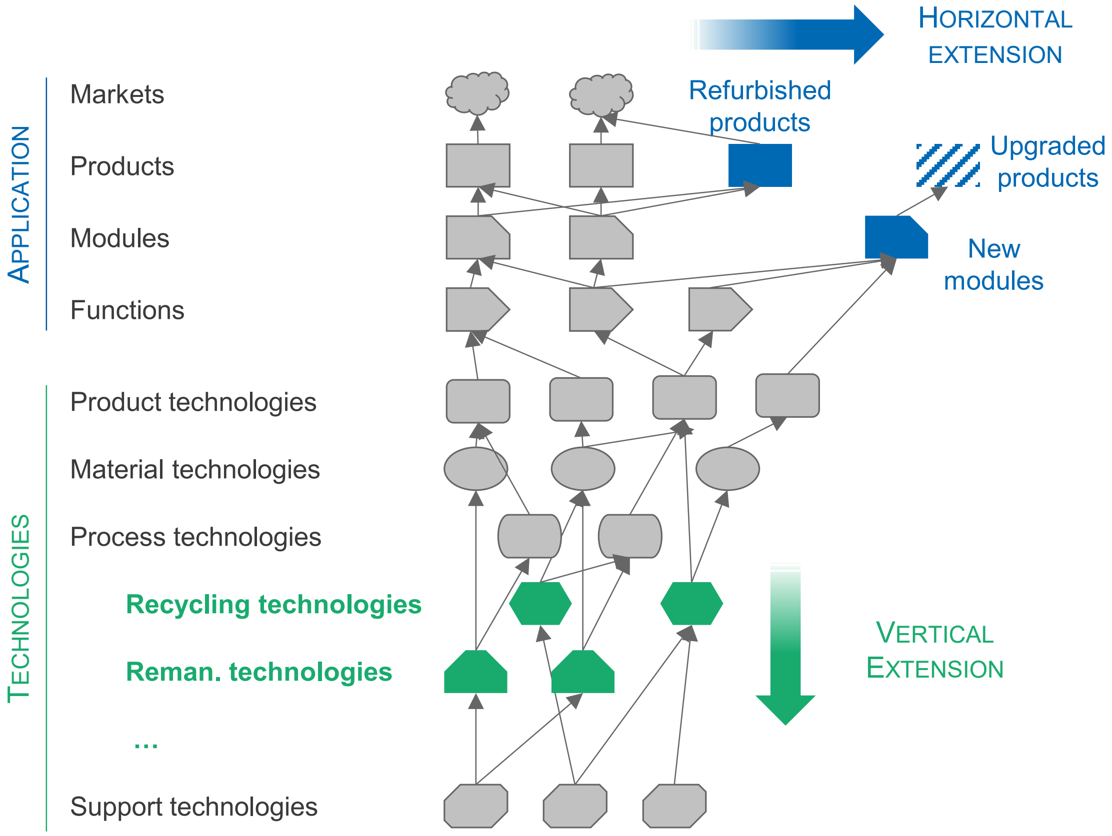

Figure 12: Schematic representation of the extension of the technology tree

Practical example: Murrelektronik GmbH

Murrelektronik is a leading company in the development and manufacture of advanced decentralized automation technology for machines and plant systems. In their efforts to optimize not only the economic but also the ecological benefits for their customers, the company is anticipating a significant technological leap in machine and plant engineering by switching from compressed air-driven to electrically driven actuators in manufacturing.

On the path to CO_2-neutral production in the automotive industry, OEMs must significantly increase their energy efficiency in their own value creation and the supply chain. One lever, particularly in body construction, is the switch from compressed air as an energy source to electrical energy for the clamping systems.

A variety of clamping systems are required in manufacturing for the automated clamping, holding and positioning of workpieces. Up to now, predominantly pneumatic clamps have *been used, which are equipped with pneumatic cylinders and use compressed air as the medium for movement. Compared to electric motors, however, compressed air systems are less efficient. This is due to the energy-intensive generation of compressed air, in which a large proportion of the energy used is lost as waste heat. In addition, due to leakages in the distribution systems and, after further conversion losses in the actuator, only a small proportion of the energy consumption is available as useful power.*

In addition to energy efficiency, the switch from pneumatic solutions to electric motors also increases the flexibility and performance of the overall system. With electric motors no longer allow only two discrete positions (e.g. open-close, forward-back), but variable positioning. Equipped with basic intelligence, the clamps can now simultaneously measure whether, for example, workpieces are correctly positioned and have the correct dimensions when gripping. This eliminates the need for additional sensors, which pneumatic clamps require today to ensure correct positioning. Ultimately, this means less wiring and thus less copper and plastic required per clamping system.

To ensure that this technological leap in automation also leads to increased benefits for the other relevant stakeholders in the value creation network, Murrelektronik has developed a concept that simplifies the overall system and thereby significantly reduces the installation effort. The newly developed installation system Vario-X is designed as a modular and highly flexible platform and enables automation functions to be implemented without control cabinets and decentral in the direct machine environment.

The centerpiece is a robust, waterproof and dustproof housing that contains the power supply, control system, bus technologies and safety technology, among other things. The installation and wiring of the sensors and actuators are carried out quickly and error-free following the plug-and-play principle. The preassembled connectors eliminate time-consuming and thus expensive installation work on the control cabinet, such as stripping, setting of wire end sleeves and clamping, for the system supplier.

Figure 13: The automation platform Vario-X

To bring such innovative products to market in short time, Murrelektronik focuses on systematically breaking down the solution to be developed into its individual functions and components and determining the technologies required for realization. This enables them to identify new technology requirements at an early stage and plan for their efficient use.

In case of the development of Vario-X as an example, this means, among other things, that the recuperation of the electric motors requires new power supply units with corresponding recuperation capability, which Murrelektronik is has specifically developed.

The modularity and flexibility requirements of the automation platform are also accompanied by the need for complex software and, in particular, control technologies. Since this will also be highly relevant for further automation solutions in the future, Murrelektronik has consciously decided to build up new competencies in the area of software technologies and thus open a new field of technology as a company.

Finally, new technologies are also being used at the material and manufacturing level. Since the company pays attention to using materials and technologies as efficiently as possible, plastic injection molding is deliberately used for dedicated housing components instead of milled aluminum parts. However, ordinary plastics generally cannot provide the required thermal conductivity, so investments have been made in material technologies to develop and industrialize an appropriate plastic.

3 Summary and outlook

Summary

The Circular Economy addresses the resource waste of conventional, linear economies by aiming for value creation without additional resource consumption. The realization of products with minimal environmental impact, the systematic recycling of products in cycles, and the simultaneous and concurrent generation of ecological and economic added value for all stakeholders reflect the core principles of this idea. However, current products are rarely suitable for a transformation to a Circular Economy. In this context, product modularization and technology planning play a central role in embedding products into a circular system. Four steps have been defined for the development of circular products, which consider product modularization and technology planning in an integrated way: First, the market and customer perspectives are taken into consideration in order to iteratively analyze customer needs over time as well as to better understand sales and raw material markets. Second, a system impact analysis is performed to anticipate future technology leaps for life cycle extension. Based on these findings, a modularization strategy is developed. Based on a system model relevant perspectives for the Circular Economy are combined and an optimization algorithm is used for a holistic modularization considering technical restrictions. Finally, in the fourth step, extended technology planning is performed with the help of a technology tree, which horizontally extends the consideration of new products to existing products, but also revised and upgraded products. Vertically, technologies for closing the cycles in form of recycling, refurbishment and remanufacturing are added.

With these four steps, a methodical approach is described that reflects the boundary conditions of the Circular Economy and applies them onto product modularization and technology planning. As a result, a basic framework for the future development of product architectures and roadmapping of the necessary technologies in a Circular Economy is formed.

Outlook: Further enablers for the transition to a Circular Economy

In addition to modularization and technology planning, there are numerous other essential prerequisites for the transformation to a circular economy: Therefore, three topics adjacent to the previously mentioned core topics of this article are outlined below as a brief outlook.

In order to ensure that a product can continue to function and be guaranteed for use in future cycles, it is important have extensive knowledge about the modules built into the product and their current condition. To obtain transparency about the use and condition of products, modules, components and materials in the Circular Economy, all relevant information generated throughout the life cycle from development and production to use and reuse must be consolidated in a digital product file. The digital product file serves as the information base for all parties involved and provides information about the relevant aspects of the product life cycle. This level of transparency about the use and condition is required for modularization in the sense of the Circular Economy. The data set includes information about the components, materials, chemical substances, reparability, spare parts, and proper disposal of the product, which is collected in all phases of the product life cycle and used for different purposes in each phase. There is a great deal of complexity involved, as each product in the field may have a different combination of original modules, refurbished modules, or modules that have already been remanufactured. Manufacturers can "record" and track the use and condition of a product using a digital product file, which is essential for remanufacturing activities. Based on the advanced digitization of products, manufacturers can predict the return of products from the field and identify modules that need to be refurbished or remanufactured early on.

The Circular Economy leads to a shift from traditional supply chain thinking towards circular ecosystems. These ecosystems require close collaboration between many different partners in a tightly interconnected network to integrate the technologies necessary. It is important to recognize that individual companies cannot close the loops by themselves but must actively build ecosystems or integrate into existing ones. Technology decisions have to consider the impact on all stakeholders involved. Decisions that are beneficial to one stakeholder may have negative impacts on others. Therefore, technology decisions must be evaluated from both an individual and a collective perspective to ensure that all partners in the ecosystem generate a benefit.

Results-oriented business models are suitable for the transformation to a Circular Economy. Due to the currently widespread transactional business models, an exchange of modules or the return and reprocessing of end-of-life products is not in the responsibility of the manufacturer. Therefore, business models that motivate customers to return the product to the manufacturer have to be considered, such as: *Buyback programs*, *deposit systems*, *service contracts* or *subscription models.* In the case of a subscription model, the products remain the property of the manufacturer and the customer only pays for the usage. Therefore, there is no return from “the market” but from “product operation” at a costumer. For this reason, subscription models are particularly suitable for use in a Circular Economy. In general, it is necessary to realize the monetization of the additional value creation with a suitable business model. This will be a central challenge in the design of future circular business models.

Key Learnings

Overall, the work of the expert group has the following implications for industrial practice: Firstly, it is fundamental to broaden one's horizon through market analyses and technology forecasts. Due to the high complexity and dynamics of technologies, it is no longer possible to plan in an all-encompassing, deterministic manner. Rather, it is necessary to anticipate scenarios and make appropriate preparations by providing flexibility for subsequent product or technology changes.

Second, the importance of Model-Based Systems Engineering or a digital twin in product development will increase significantly. Access to technology and digital solutions is essential in today's world to develop successful products. It is also crucial to integrate existing knowledge and opportunities continuously into the development process. Additionally, the ability to capture and evaluate usage patterns and product histories is vital. Furthermore, architectural decisions must be evaluated based on the potential for future monetization through improved sustainability. Finally, it is important to keep raw materials circulating in different levels of processing, leading to more complex circular value creation structures.

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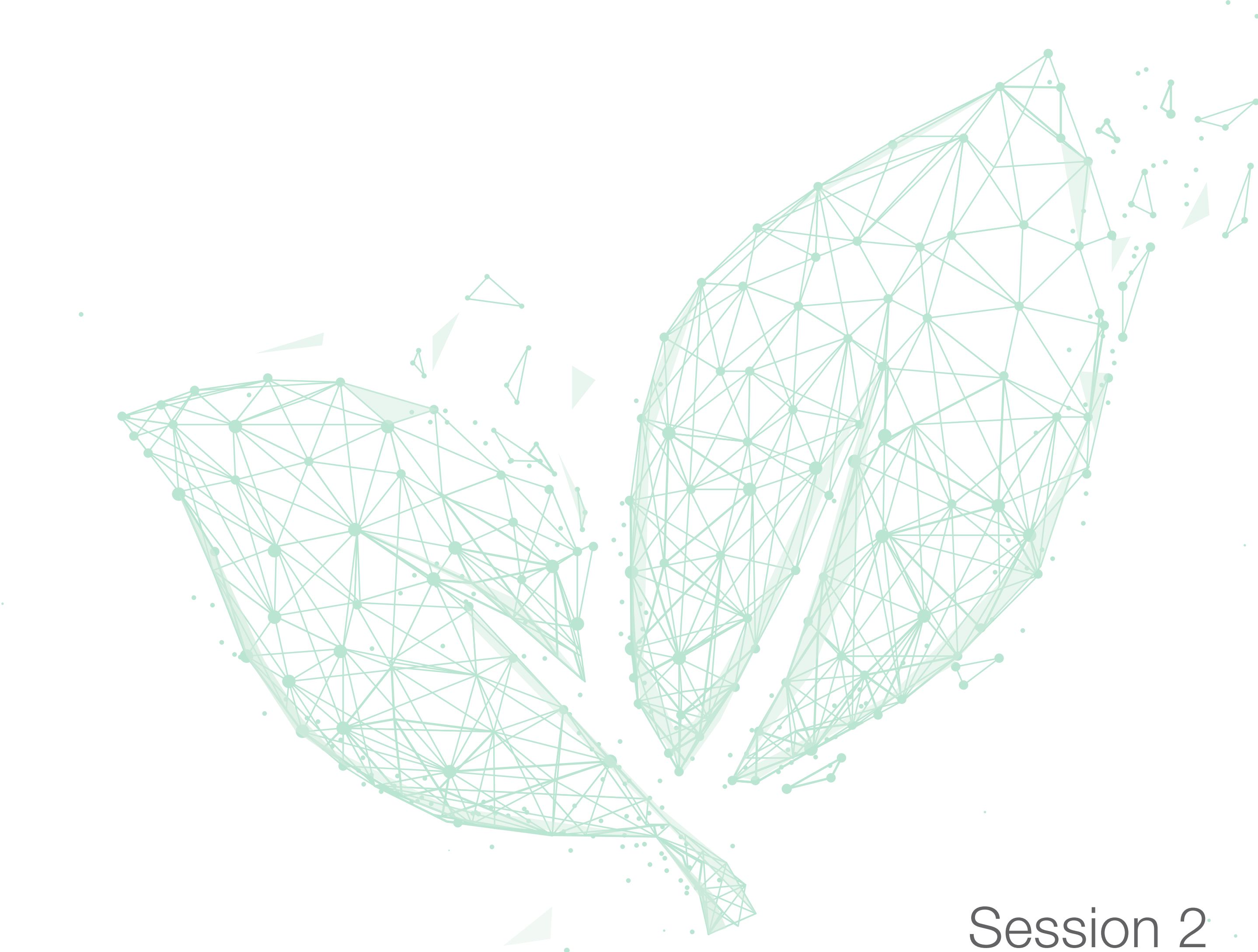

Session 2
Resource efficient manufacturing

2.1 Manufacturing for a Circular Economy

T. Bergs, J. Brimmers

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Abstract

Manufacturing for a Circular Economy

The sustainable use of the earth's resources forms the essential goal of our society. For industry, and in particular for manufacturing companies, this poses completely new challenges in the design of resource-conserving value chains in the sense of the circular economy and the rapid realization of sustainable products. The successful implementation of the circular economy in manufacturing companies requires different approaches - the consideration of the environmental impact of the manufacturing process, the optimization of the manufacturing-related product properties, the analysis of the correlation between production and use as well as the development of new business models to maintain or increase value. For this purpose, the digital twin represents the necessary tool or the enablement for a successful implementation of these approaches. At the same time, the digital twin is also the essential enabler for the rapid development of manufacturing processes for the provision of sustainable products. For both of these approaches, this paper presents various examples that are used to demonstrate the possibilities and perspectives of sustainable manufacturing. Furthermore, recommendations for action for the implementation of a circular economy for manufacturing companies can be derived from the examples.

Keywords: Circular cconomy, Sustainable production, Digital twin, Production of sustainable products

Kurzfassung

Fertigung für eine Kreislaufwirtschaft

Die nachhaltige Nutzung der Ressourcen der Erde bildet das wesentliche Ziel unserer Gesellschaft. Für die Industrie und insbesondere produzierende Unternehmen ergeben sich dadurch völlig neue Herausforderungen in der Gestaltung ressourcenschonender Wertschöpfungsketten im Sinne der Kreislaufwirtschaft sowie der schnellen Realisierung nachhaltiger Produkte. Die erfolgreiche Implementierung der Kreislaufwirtschaft in produzierenden Unternehmen bedarf dabei verschiedener Ansätze - die Betrachtung der Umweltwirkung des Fertigungsprozesses, die Optimierung der fertigungsbedingten Produkteigenschaften, die Analyse der Korrelation zwischen Produktion und Nutzung sowie die Erarbeitung neuer Geschäftsmodelle zur Werterhaltung bzw. –steigerung. Der digitale Zwilling stellt hierfür das notwendige Werkzeug bzw. die Befähigung für eine erfolgreiche Umsetzung dieser Ansätze dar. Gleichzeitig ist der digitale Zwilling auch der wesentliche Befähiger für die schnelle Entwicklung von Fertigungsprozessen für die Bereitstellung nachhaltiger Produkte. Für diese beiden Ansätze werden in dem vorliegenden Beitrag verschiedene Beispiele vorgestellt, anhand derer die Möglichkeiten und Perspektiven einer nachhaltigen Produktion aufgezeigt werden. Ferner lassen sich aus den Beispielen Handlungsempfehlungen für die Umsetzung einer Kreislaufwirtschaft für produzierende Unternehmen ableiten.

Schlagwörter: Kreislaufwirtschaft, Nachhaltige Produktion, Digitaler Zwilling, Produktion nachhaltiger Produkte

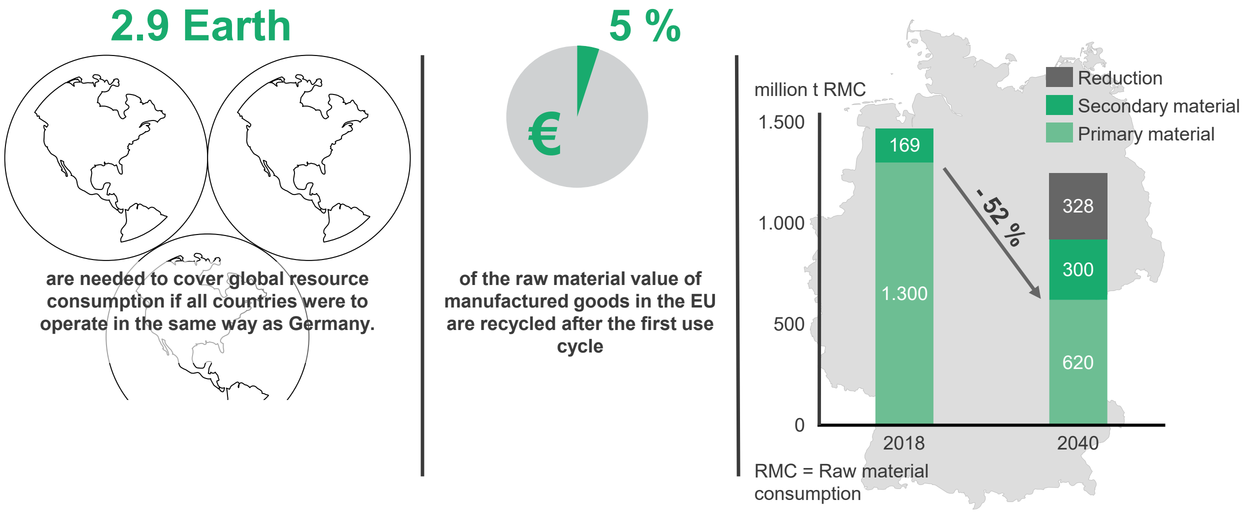
1 Introduction

The sustainable use of resources on our planet is the major goal of our and future generations. In 2015, the United Nations jointly set 17 goals under the title *Sustainable Development Goals* (SDGs) [1]. In particular, Goals 9, 11, 12, and 13 highlight the need for innovative and sustainable products for the future, cf. Figure 1.

Figure 1: Sustainable Development Goals of the United Nations

The *Green Deal,* adopted by the European Union in 2020, identifies climate neutrality in 2050 as a necessary goal and picks up on the United Nations target [2]. The European *Green Deal* focuses in particular on the circular economy. It formulates 35 action points, which promote the implementation of the circular economy through a variety of measures. The design processes of sustainable products and the development of sustainable production processes are derived from the *Green Deal and* describe the objectives for the manufacturing industry. The urgency of implementation is shown in Figure 2 illustrates the urgency of implementation. The current resource consumption in Germany corresponds to the available renewable resources of 2.9 Earths. It also shows that the resource consumption of primary raw materials must be reduced by 52 % by 2040 in order to achieve the climate targets.

This topic has been the subject of many scientific publications in recent years. However, the approaches presented in the scientific publications are mainly of a methodological nature. [3]. This is due, among other things, to the numerous challenges to the implementation of a circular economy in the previous value system [4]. However, the topic of the circular economy shows a high relevance for the achievement of the SDG targets and thus also for the European Union's *Green Deal* [5].



Sources: UBA22; Ellen MacArthur Foundation15; Circular Economy Initiative21

Figure 2: High resource consumption requires a rethink by the industry

The question of what challenges exist from the point of view of a manufacturing company and what measures can be taken to achieve a circular economy for technical products in the short and long term forms the core of this article. To this end, the first part of the article first provides an introduction to the topic, focusing in particular on the manufacture of higher-value, technical products. The digital twin is highlighted as an enabler for an effective implementation of the circular economy and the challenges for its implementation are outlined. Subsequently, various application examples for the implementation of a circular economy are presented from the perspective of manufacturing companies.

2 Manufacturing in the circular economy

The concept of circular economy represents a key solution approach for industry to achieve climate goals [5]. From the point of view of manufacturing as an important phase in the product life cycle, it is therefore necessary to provide a classification of the topic of the circular economy in steps. For this purpose, the existing definitions and concepts of the product life cycle and the circular economy are summarized below and examined from the perspective of a manufacturing company.

2.1 Classification

Product life cycle

The life cycle of a product covers the following five phases, which are shown on the left in Figure 3 are shown [6], [7]:

- Product idea
- Product design and development
- Product manufacturing and assembly
- Product usage
- Product end of life

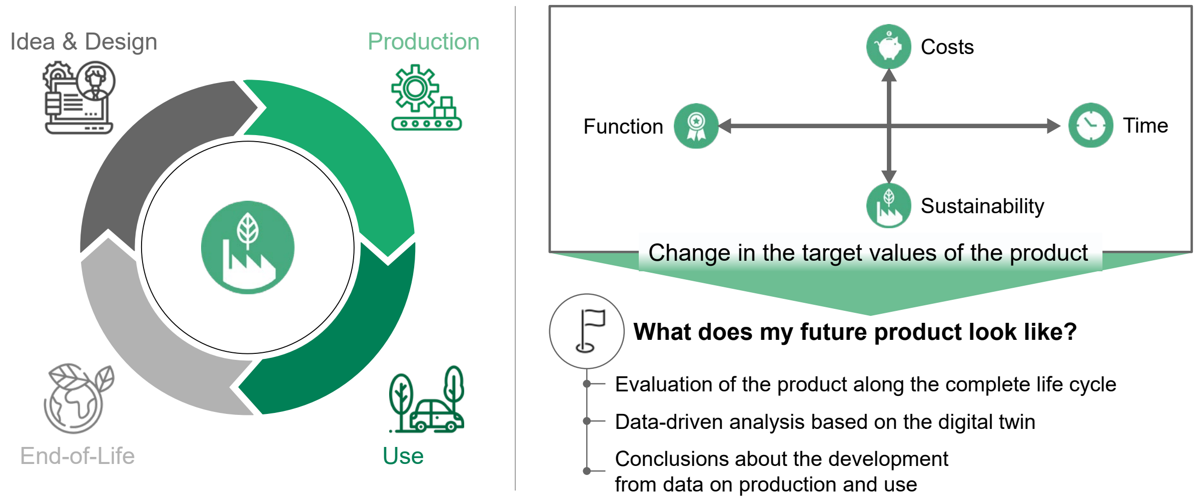


Figure 3: Product life cycle and changing targets for product development, production and use

Depending on the type of product, different requirements are placed on the five phases in the product life cycle. These requirements result, for example, from existing regulations and statutory provisions, from customer demands and the existing competitive situation in the market. The requirements placed on the product are converted into product functionality or product properties in the product development phase.

These product functionalities or properties must be ensured in the product manufacturing and assembly step. Up to now, production has been faced with conflicting goals in terms of functional fulfillment, costs and production time. In order to ensure that the announced climate targets are met, see chapter 1, sustainability will also have to be taken into account in the future, see right-hand side of Figure 3. It is therefore necessary to reduce both the ecological footprint of the product and the ecological footprint of the production process. This can be achieved, for example, by using renewable energies and renewable or recycled raw materials.

Product use is generally the longest phase in the product life cycle. The most important target variables here are product availability in terms of functionality and operating costs. In the future, an ecological evaluation of product use will also have to be carried out. It should be noted here that the sustainability of a product during use is already significantly influenced in the development phase and the production phase [8]. For example, the efficiency of a gearbox can be significantly influenced by the surface finish of the gears. The definition of this surface condition takes place in the development process, whereas the generation of this surface is completed in the production phase, which is sometimes energy and resource intensive. This illustrates that an objective sustainability assessment requires not only the singular consideration of the individual product life phases, but rather the holistic consideration of all phases of the product life cycle.

The end of product life marks a milestone in the product life cycle. The end of product life is defined as the point in time when the product can no longer fulfill the required product functionality. A distinction can be made between end-of-use (EOU) and end-of-life (EOL) [9]. EOU describes the state in which the product can again fulfill the intended functionality at least partially through a targeted measure, whereas EOL describes the complete end of life of the product. When the EOL is reached, the only remaining option is to return the products to the cycle in the form of recycling processes or other methods of material recovery. In addition to the actual EOU or EOL of a product, there is also a product lifetime, which serves as a target value for the development phase. Depending on the product type, the product life can be measured in operating hours, kilometers or load cycles, for example. The objective of a sustainable product in a circular economy is therefore to maximize its service life in terms of EOL or EOU. At this point, the particular importance of the manufacturing method used should already be mentioned, as this is largely responsible for the longevity as well as the efficiency of the product. Its design against the background of maximum resource efficiency will be the focus of this article later on.

Circular economy

The concept of circular economy represents the operationalization of the implementation of a sustainable product [4]. The understanding of the term circular economy for this report is based on the interpretation of the term according to Kirchherr et al. [4]. The goal of the circular economy is to extend the concept of EOL by reducing (Reduce), reusing (Reuse), recycling or recovering (Recover) material in the production, distribution and use phases [3], [4]. The concept of circular economy finds implementation at several scales: macro (production system level), meso (sector level), micro (company level), and nano (product level) [10]. Similarly, the circular economy covers aspects of economic, environmental, and social sustainability [4]. However, from the perspective of production and manufacturing companies, the concept of sustainability is interpreted with a focus on environmental sustainability [3].

In the implementation of the circular economy, the literature distinguishes between different frameworks/classifications. These classifications differ in the granularity of the possible strategies and are referred to as R-scenarios. In the literature, a distinction is made between 3R [11], 4R [12], 6R [13] up to 9R [14]. The nine scenarios according to 9R are shown in Figure 4 shown.

The nine R scenarios can be divided into three main classes. The strategies Refuse (R0), Rethink (R1) and Reduce (R2) require a new and innovative product development and production. Refuse (R0) leads to a reduction of product variety by separating functions or to a radical and innovative redesign of the product with the previous range of functions. Rethink (R1) describes the rethinking of the use of existing products and thus the increase in the utilization of a product by, for example, expanding the circle of users through sharing concepts (car sharing, subscription models, etc.). The Reduce scenario (R2) coincides with the familiar basic idea of process and product optimization, whereby costs and production time have been used primarily as optimization parameters in the past and sustainability or the ecological footprint should also be taken into account as a target parameter in the future.

The second class comprises the scenarios Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6) and Repurpose (R7). These scenarios have in common the basic idea of extending the product life and thus postponing the EOU or EOL to a later point in time. Reuse (R3) describes the possibility of continued use of the existing product with the same functionality by another user or entity. The prerequisite for this is that the existing product is still in a usable condition and the functional fulfillment is ensured. Repair (R4) is the repair and reconditioning of a defective product so that the actual function can be fulfilled again. Refurbish (R5) describes the repair and simultaneous update of an existing product, whereby in some cases newer or higher-quality subcomponents can be installed or the range of functions expanded or renewed. Remanufacture (R6) describes the use of still usable subcomponents of a defective product to create a new product with the same function. It is also possible to manufacture completely new subcomponents. Repurpose (R7) follows the same idea of reusing subcomponents, but with the aim of creating a product that fulfills a different function than the product from which the subcomponents were removed.

Classes	R scenarios	Implementation
Innovative products & processes	R0 Refuse	Make product obsolete or radically rethink it
	R1 Rethink	Increase and rethink product use (e.g., sharing)
	R2 Reduce	Reduce resource use in product or production, increase efficiency
Extension of the product life cycle	R3 Reuse	Further use by third parties without adaptation of the product
	R4 Repair	Repair and restoration of the actual product function
	R5 Refurbish	Repair and update of a product
	R6 Remanufacture	Use of parts from defective products in a new product with the same function
	R7 Repurpose	Use of parts from defective products in a new product with different functions
Material usage	R8 Recycle	Further processing of the materials in the same or lower quality
	R9 Recover	Utilization of the materials (e.g. thermal utilization for electricity generation)

Increase sustainability

Figure 4: 9R scenarios in the circular economy as depicted in [4], [14]

The third class contains the scenarios Recycle (R8) and Recover (R9). In this class, the product can no longer be used, so the focus here is on the material. Recycle (R8) describes the recovery of the materials either in the same or in reduced material quality. These materials can then be reused for the production of new products. Recover (R9) represents the last option for a product, as here the material used cannot be reused. Therefore, for example, only the possibility of thermal recycling arises. This scenario characterizes the state with the lowest potential of sustainability. As shown on the left in Figure 4 shown, the potential benefits of the circular economy increase in reverse order from Recover (R9) to R0 (Refuse). The Recycle (R8) and Recover (R9) scenarios currently represent the status quo in many industries, but these approaches are characterized by low value retention. Therefore, the goal in the future should be to pursue the R7-R0 scenarios so that a higher value retention or even an increase in value for the products can be achieved.

In the quantification of the ecological footprint of companies and organizations, a distinction is made between so-called "scopes" or emission areas [15]:

- Scope 1: This refers to direct GHG emissions from sources within the control of the company or organization, such as emissions from the combustion of fossil fuels in company-owned facilities or vehicles.
- Scope 2: This refers to indirect GHG emissions resulting from the generation of purchased electricity, heating or cooling used by the company or organization. These emissions occur outside the direct control of the company or organization, but can be reduced by purchasing renewable energy.
- Scope 3: This refers to all other indirect GHG emissions that arise in connection with the activities of the company or organization but are outside the control of the company or organization. This can be, for example, emissions from the production

of raw materials, from the disposal of waste, or from the use of products and services.

In particular, manufacturing companies that are part of a value chain without their own responsibility for the subsequent product face the challenge of quantifying the resulting GHG emissions in Scope 3, i.e., including upstream and downstream process steps. Here, there is often a lack of access to data from these upstream and downstream stages of the value chain in order to determine the scope 3 impacts mathematically.

Overall, the scope for action of manufacturing companies, especially those with product responsibility, OEMs in business-to-customer (B2C) or production equipment suppliers, toolmakers in business-to-business (B2B), is diverse, as there is corresponding scope for cross-lifecycle optimization measures in the sense of a holistic view of sustainability. If, on the other hand, one takes the perspective of a manufacturing company, e.g. component manufacturer within a value chain, the design options are significantly more limited, which is due to the aforementioned lack of access to corresponding data outside of one's own value creation stages or life cycle phases. With reference to the aforementioned R-scenarios, four key sustainability approaches emerge for manufacturing companies from a manufacturing perspective. These four approaches are shown in Figure 5.

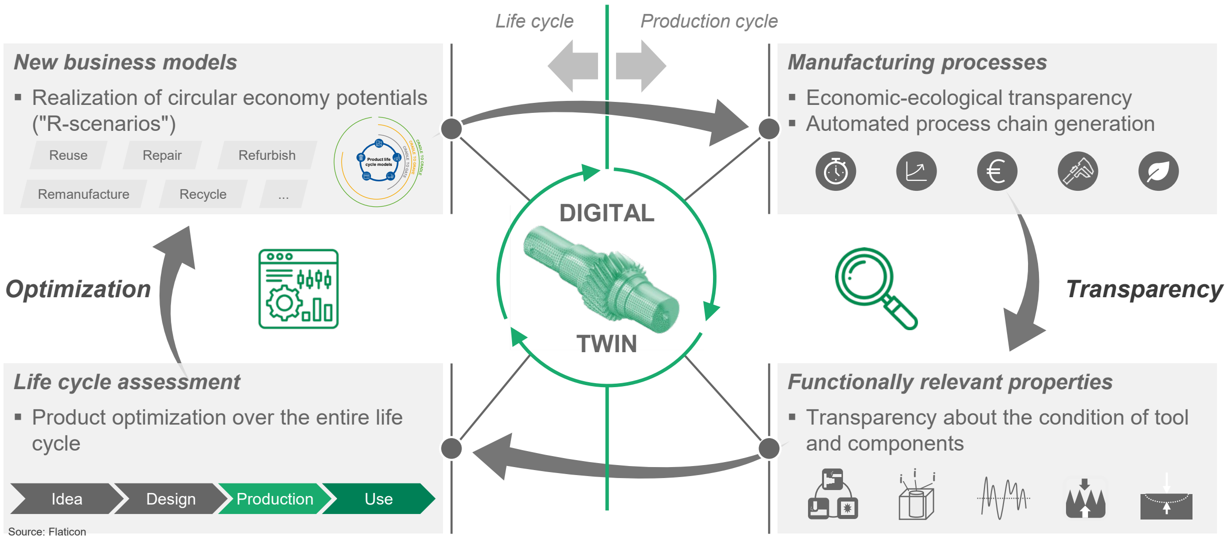


Figure 5: Sustainability approaches for manufacturing companies

The first approach, top right, describes the transparent and ecologically sustainable design of manufacturing processes and their optimization. For this approach, R-scenarios from the first and second class are used (R0 - R7). Whereas manufacturing costs and times were previously the focus of an evaluation and optimization, the ecological effects are now also included. For this purpose, the input and output variables used, such as material input (workpiece and tool materials), operating materials and the energy required for each process and across the process chain, must be considered and evaluated. Here, reference should already be made to the importance of the digital twin, which provides the necessary transparency and thus access to the relevant information on a component-by-component basis. In the future, the digital twin will also provide an evaluation basis for increasingly flexible and automatable assembly and manufacturing processes, which will allow cost-effective machining of highly individualized components, for example in a repair process. [16]. The main focus here is on reducing the manual effort required, for example, for an initial diagnosis of defective products, as a starting point for adapted ecologic production planning. Here, too, the digital twin will be a necessary prerequisite in the future.

The second approach, bottom right, deals with the targeted generation of production-related functionality and functionally relevant properties of the products. The basis for this approach is increased information transparency with regard to the effect of the manufacturing process on the product - again with the help of the digital twin. With regard to the R scenarios, this approach can be assigned to the Reduce (R2) scenario. However, this presupposes knowledge on the part of the component manufacturer about the effect of the generated component functionality on the later component use. For example, a component surface can be specified which results in lower power loss in the tribological system due to reduced friction and thus in higher efficiency in component use. In the same way, innovative and new manufacturing technologies can be used to create product properties that may not have been possible with previously known processes. In the future, these new product properties could also lead to an increase in efficiency and a reduction in the amount of material used for new products.

The description of the functionally relevant properties in the digital twin enables the scope of consideration to be extended to the life cycle of the product under consideration. This third approach, bottom left, ultimately creates the information basis for carrying out holistic life cycle product optimization with the help of suitable life cycle assessment (LCA) methods. The balancing methods thus enable the ecological and economic footprint of the product to be quantified and form a further important assessment basis for the manufacturing company. Based on these characteristic values, an optimization of the product can take place. This also allows innovative approaches to be evaluated on the basis of the R-scenarios (R0 - R9) for maintaining or increasing the value of the product, and new business models to be realized (fourth approach, top left).

The new business models result in changed challenges for the production of products. This changes the focus from the life cycle to the product cycle and results in further approaches for optimizing production technology to increase sustainability in manufacturing companies. What the four approaches have in common is that the chance of success depends heavily on the availability of usable data. The four approaches can only be successfully implemented with high-quality data on the product, production and the usage behavior of the product users. Therefore, the digital twin is the essential enabler to implement these four approaches profitably in the producing company.

2.2 The digital twin as an enabler for the successful implementation of the circular economy

The approaches described above for implementing the circular economy in manufacturing companies require the availability of different information in all phases of the product life cycle. This is achieved in the form of the digital twin already mentioned, which can provide both the technical condition of the product along its life cycle and the resources used in the process, often referred to as a rucksack. In principle, the digital twin is understood as a digital representation of a real object which undergoes a process-related change of state during production [17]. Individual manufacturing processes cause changes between individual time-discrete states of the digital twin and influence function-determining properties [17]. Thus, it is possible to analyze the individual processes, process chains in their effect on the function-determining properties as well as on the ecological key figures in more detail. Taking this idea further, the digital twin can be used to integrally bring together relevant data from the development phase, the production phase, through to the use and EOL phases, and to perform a holistic assessment of sustainability.

Even at the end of the utilization phase, the necessary information about the product's condition is available to enable further material recycling in the sense of the R-cycles.

The essential functions of the digital twin from the perspective of a manufacturing company are shown in Figure 6. In addition to a single-process-specific focus (vertical level) of the digital twin, the linking of several individual processes to form a process chain (horizontal level) is also represented by the digital twin of the product, see figure on the left. For the implementation and use of the digital twin in manufacturing, special attention must be paid to four aspects.

The first aspect comprises the essential tasks for data acquisition and connectivity. This includes the acquisition and structured storage of heterogeneous data along the life cycle of the product. The data to be stored varies from product to product and is primarily based on the relevance of the data for the subsequent fulfillment of the product's function [17]. This can be understood as a requirement specification, which brings together the totality of the requirements for the product and thus specifies the scope of the data to be collected [17]. Likewise, this data forms the basis for the analysis and optimization of the individual process or the process chain and its interactions. The information transparency created by the digital twin is reflected in the first approach to increasing sustainability in manufacturing processes, cf. Figure 5 top right.

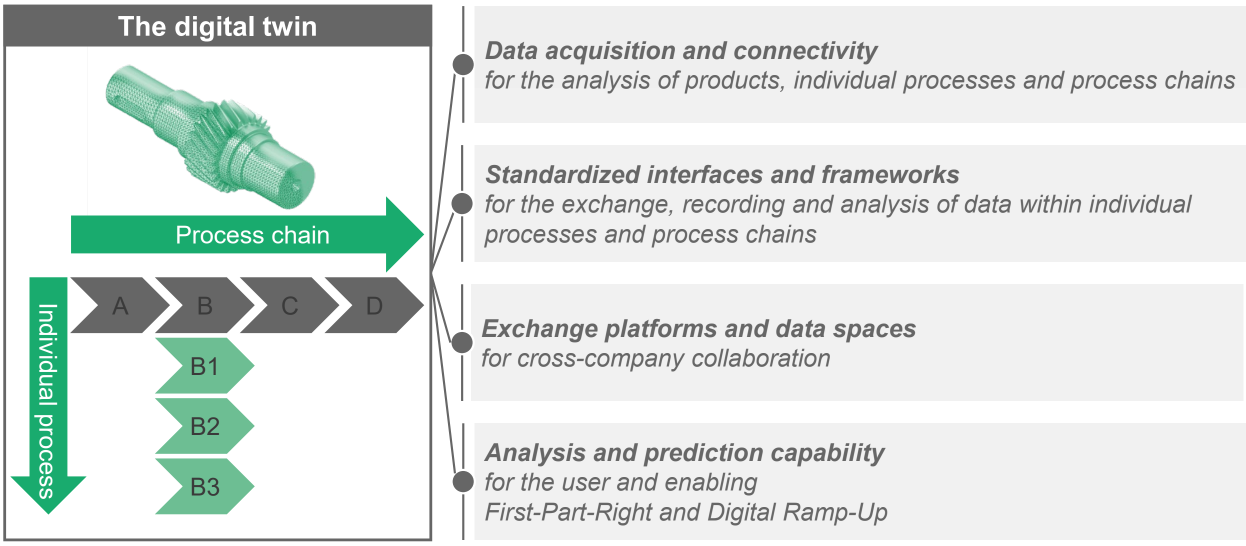


Figure 6: Prerequisites for the implementation of the digital twin as an enabler of the circular economy from the manufacturing perspective

Another prerequisite is the provision of standardized interfaces and frameworks within a process and along a process chain. In both cases, this ensures that data from a wide variety of data sources and formats can be exchanged, recorded and analyzed. For example, data can be exchanged internally within a company without the risk of misinterpretation of the data or the information derived from it. As a result, the functionally relevant properties of the product can be described unambiguously, cf. Figure 5 bottom right.

For the creation and use of the digital twin, there are already initial initiatives to create standardized formats and architectures. For manufacturing, for example, the digital twin framework according to ISO 23247 has become established [18]. This framework is based on a Lambda architecture and has different layers and domains. In addition to the batch layer for processing large amounts of data, the stream layer is the prerequisite for real-time capable processing of data packets. The framework builds on the following four domains [17]:

- User domain: people, devices, systems that use applications and services from the core domain
- Core domain: operation and management of the digital twin (provisioning, monitoring, optimization, etc.)
- Data collection domain: monitoring and collection of sensory data
- Observable manufacturing domain: Physical manufacturing resources such as personnel, equipment, material, etc.

With the help of this framework, a standard for the implementation of a digital twin within a manufacturing company should become possible in the future.

In addition to such initiatives, there are already standardized data formats which can be used within the digital twin for data storage and also for data exchange at defined points in time. One example of such a data format is the Gear *Data Exchange* (GDE) format in the field of gear manufacturing. This format is defined according to VDI 2610, is based on the Extended Markup Language (XML) and exists since 2018 [19]. Using this format, the geometry, the desired manufacturing tolerances, the measurement instructions, as well as measurement results and the manufacturing processes can be documented in a component-specific manner. This standardized file format can thus be used to exchange data between machines (e.g. gear grinding machine and gear measuring machine for automatic manufacturing correction) but also across companies (gear cutting machine and tool manufacturer for tool production). The defined contents and the standardized interpretability of the data ensure error-reduced processing of the data.

Current initiatives to create collaborative data ecosystems and cross-company exchange platforms go one step further. One well-known representative of a collaborative data ecosystem is the *Catena-X* platform. *Catena-X* is an association of numerous companies in the automotive industry. The vision is to provide a collaborative, open and secure data ecosystem that connects the different players in the value chains within automotive production, ensures data sovereignty over their own data, enables accelerated digitization of processes even for small and medium-sized companies, and promotes cooperation and collaboration between market participants and competitors [20]. The *Manufacturing-X* initiative, which is currently being established, builds on the model of *Catena-X* and aims to transfer the approaches from *Catena-X to* other industrial sectors (mechanical engineering, chemicals & pharmaceuticals, food, electronics, etc.) [21]. Especially for the use of the digital twin in the sense of the circular economy, such platforms represent important prerequisites. They create the necessary data transparency for all parties involved for the evaluation of the ecological footprint of the product, even across life cycles. This coincides with the requirements for the previously mentioned approaches to sustainability, cf. Figure 5 bottom left.

The fourth prerequisite describes the user perspective of the digital twin and addresses the actual analysis and forecasting capability through the use of the digital twin. For manufacturing companies, the approaches to quality-controlled production in accordance with the goal of "*first part right*" and digital support of the start-up process ("*digital ramp-up*") are of particular relevance. Likewise, further fields of application and business models for the products can be devised on the basis of improved forecasts. This forms the prerequisite for the approach in Figure 5 top left.

Predictive capability in the sense of *first part right* is made possible in particular by linking physical models with sensory measurement data from the process or from the process chain in the digital twin. Based on this information, it is possible to intervene in the process if the desired quality for the production step cannot be achieved. Likewise, historical data from previously manufactured components can be used to improve the quality of the physical models and thus increase the predictive quality of the quality prediction.

The approach to digitally support the start-up process represents a strong competitive advantage, especially in the future, in a successful implementation for the production of sustainable products. This approach enables a significant acceleration of the start-up process of a series production with simultaneous cost reduction. Crucial for the cost reduction is the possible reduction of experimental investigations and validation tests. The number of necessary experiments can be reduced on the basis of extensive simulative studies with the digital twin and reduced to essential experiments to verify the approaches and to demonstrate the most important influencing factors. It is precisely these cost- and time-reducing measures that enable rapid provision of manufacturing capacities for new products and rapid responsiveness in the case of modified products.

2.3 Current challenges for the implementation

In the previous sections, approaches for implementing the circular economy in manufacturing companies were presented and the digital twin was identified as an enabler for the successful implementation of these approaches. In the following, we will discuss the challenges that currently impede the implementation of the aforementioned approaches to the circular economy.

An overview of existing challenges is presented in Figure 7 is given. From the literature and from discussion with industry, these challenges can be divided into six focal points.

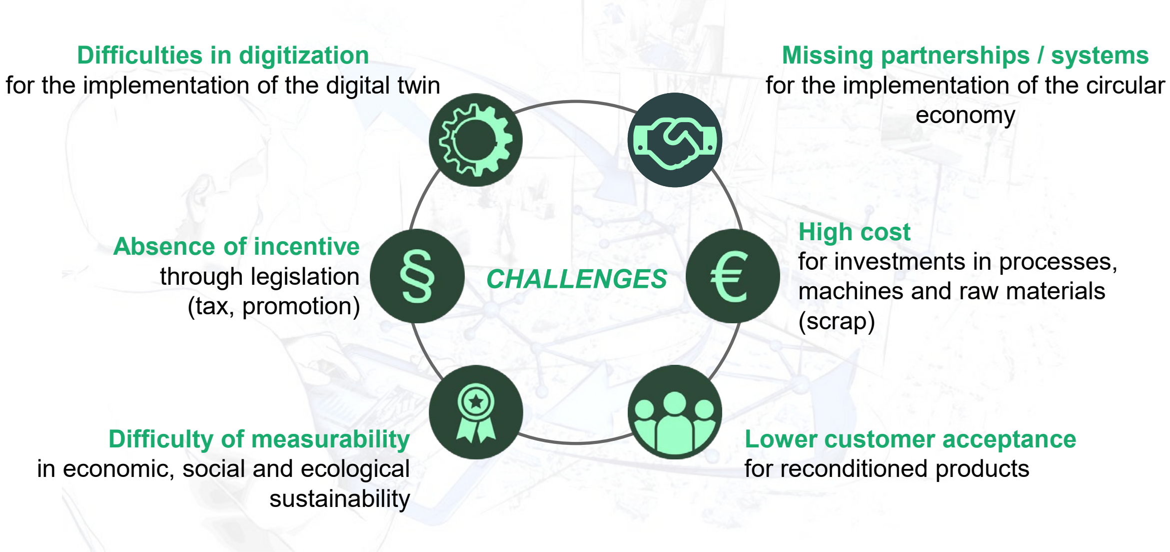


Figure 7: Current challenges for the implementation of the circular economy in manufacturing companies

The first challenge is the difficulty in implementing the digital twin. Major problems arise for manufacturing companies in the structured recording of data. This applies in particular to manufacturing companies that have very heterogeneous machinery. There are currently no completely standardized interfaces and data formats available that would enable a generally valid definition of the relevant data. Instead, each machine has different formats for import and export and different specific definitions of process parameters or axis configurations. This makes the implementation of digitization more difficult and requires a very high level of personnel. Especially for small and medium-sized companies, this required personnel deployment cannot be mapped, since in most cases adequately qualified personnel is also lacking and thus employees must be further trained or newly hired in the first step.

A second challenge is the lack of partnerships and systems for implementing the circular economy [3]. Especially for manufacturing companies without product ownership, this represents a major challenge due to the lack of information transparency across companies. Initiatives such as *Catena-X* have recognized this problem and are developing suitable solution methods. However, trust between suppliers and customers in particular must be strengthened with regard to information sharing and the benefits of information sharing must be brought to the fore and increased.

The third challenge is the high cost of implementing a circular economy [3]. Process and supply chains need to be rethought and adapted, requiring investment in new machinery and equipment. Similarly, the availability of sustainable energy and sustainable raw materials at low cost is another problem.

Further challenges are the currently still lower acceptance of end customers for "non" new products and goods [16], the low public availability of sustainability metrics of companies or products [3] and the lack of incentive to implement sustainability strategies by legislators [3].

3 Perspectives for manufacturing in a sustainable economy

In the preceding sections, key building blocks and approaches for realizing a circular economy were discussed. The digital twin was identified as a key enabler, although a large number of challenges still hinder the implementation of the circular economy. In the following, perspectives for the implementation of the circular economy from the point of view of a manufacturing company are presented by means of examples. These examples can be categorized as *sustainable production*, using the different sustainability approaches according to Figure 5, as well as the category of *production of sustainable products* with new or adapted manufacturing processes. The latter primarily address the aspect of "digital ramp-up" - i.e., the rapid scaling of sustainable and, above all, competitive *production of sustainable products*. An overview is provided by Figure 8.

In this article, the *sustainable production* category is based on the four approaches to increase the sustainability presented. Three examples are presented below. The examples include the technological and ecological consideration of a process chain for gear manufacturing and two examples of manufacturing technologies that demonstrate new business models for the R scenarios Repair and Remanufacture. The assignment to the respective sustainability approaches for each example is made via the pictogram at the top left.

The second category comprises the *production of sustainable products*. Here, the focus is on competitive manufacturing of new products, innovative manufacturing processes, flexible and scalable manufacturing chains, and digital ramp-up. Three examples are presented for this category. The examples show that the digital twin is a necessary prerequisite for the production of sustainable products.

Finally, a vision for the marketplace for semi-finished products is presented. The market-place should enable and simplify the further use of technical components in new products.

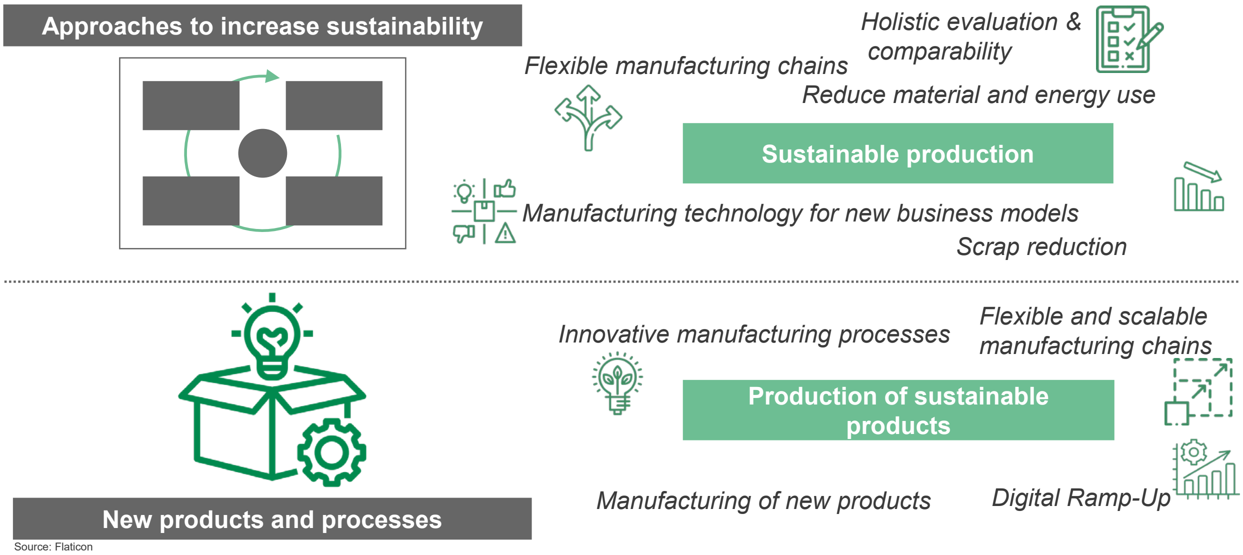


Figure 8 : Perspectives for manufacturing in a sustainable economy

3.1 Examples and perspectives for sustainable production

In this section, examples and perspectives for the s*ustainable production* category are given. These examples address at least one sustainability approach for manufacturing companies, cf. Figure 5.

The first example can be assigned to the three approaches of transparent manufacturing processes, consideration of functionally relevant properties, and holistic assessment over the life cycle. These approaches are shown in the example of the production of a geared pinion shaft for a transmission from an electrically powered vehicle, see Figure 9. The example was implemented as a demonstrator at the Laboratory for Machine Tools and Production Engineering WZL | RWTH Aachen University.

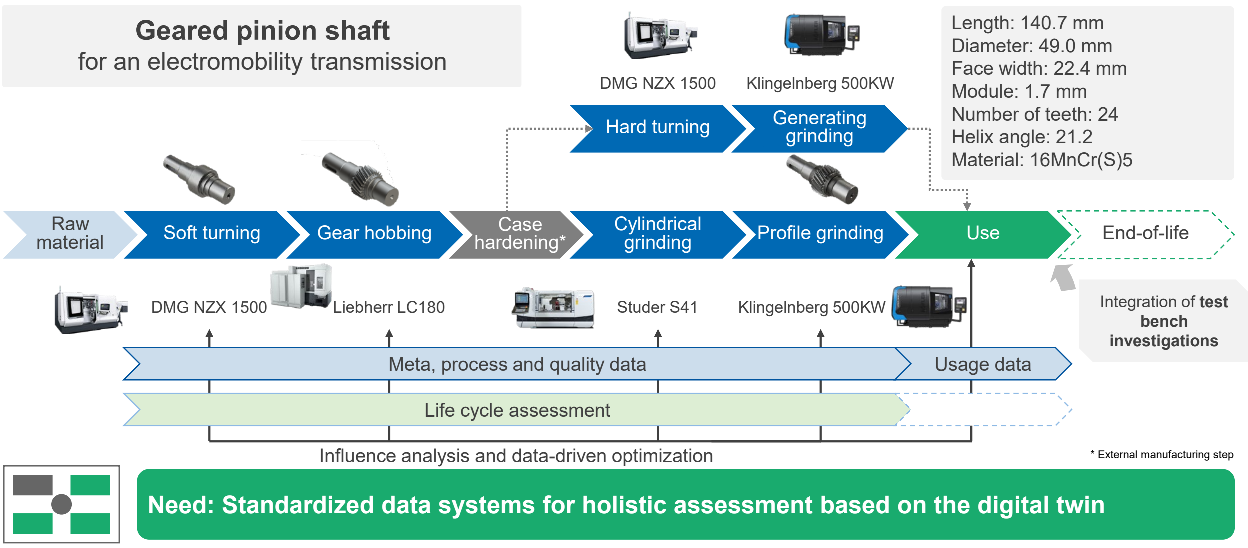


Figure 9: Sustainability assessment of components using the example of a gear from electro-mobility

The holistic ecological and economic evaluation of a product, such as the geared pinion shaft shown, requires a corresponding digital twin for each processing step of the product. This digital twin is fed from different data sources and describes all relevant product properties. For the ecological assessment, these are the data on the current energy consumption of the production machines (in this case electricity) and on the substances used (raw material, tool material, cooling lubricant, compressed air, etc.). It is also interesting to know how much material is machined in which production step and how much energy has to be used for this step. By means of this survey, process steps can be identified which show an unfavorable ratio between cutting performance and energy consumption. However, this analysis cannot be carried out without taking into account the component quality to ensure function as well as the resulting manufacturing costs. Sustainable production in the future can therefore only be considered as a compromise between the component quality achieved, the process or product costs and ecological sustainability.

For the geared pinion shaft example shown, the production chain consists of the following steps:

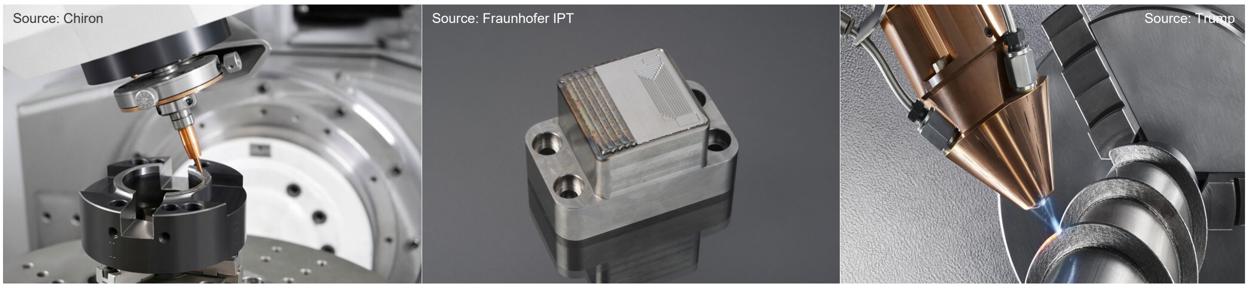
- Turning the outer contour
- Soft machining of the gear via gear hobbing
- Heat treatment (case hardening)
- Hard machining of the functional surfaces
- Hard machining of the gear

In order to shed more light on the above-mentioned compromise, a test plan was drawn up by varying the four substeps mentioned in the manufacturing process. Thus, either process parameters were changed or different manufacturing technologies (profile grinding to generating grinding) were compared. In addition, these parts were examined on the test rig to determine a statement about the mappability of functional properties through different process chains in combination with the resulting operational behavior. To this end, for example, gear noise vibration and harshness (NVH) were investigated using single flank tests to establish a correlation between component quality and component function. Likewise, the load-bearing capacity of the gearing was investigated with regard to a possible correlation. The load-bearing capacity can be used to estimate an expected service life in the later use phase. Results from the analysis of the process chain and the service life phase show that functional properties can be achieved independently of the process. Similarly, it was found that simultaneous optimization of the environmental footprint does not equate to a deterioration in the economics of the process. Further evaluations will be presented during the lab tours at the WZL | RWTH Aachen University.

The main challenge in implementing this project was making the data available and creating the digital twin. The multitude of different production machines and production technologies forms a heterogeneous landscape as a basis for digitization. In the implementation of the demonstrator, it was possible to homogenize the data and make it available for use in the digital twin. This made it possible to perform the analysis and LCA.

Uniform conventions for data formats and frameworks are therefore required for simple implementation of the digital twin in the future. In the case of cross-company production chains, uniform data ecosystems are also necessary to ensure information transparency (e.g., Catena-X). This is the only way to ensure that existing knowledge can be transferred from process to process and that the effort required to implement a new process can be greatly reduced. This ensures that the functional properties and thus increased efficiency and sustainability of the product can be achieved.

The achievement of functional properties is also relevant for the following example. Here, manufacturing technologies for automated component repair are presented, see Figure 10. This example is assigned to the approaches of transparent manufacturing processes, the consideration of functionally relevant properties and new business models.



Manufacturing technologies, such as

... Laser Metal Fusion (LFM)

... Laser Metal Deposition (LDM)

offer the possibility of component repair.

+ Repair possible on original component
+ Significant reduction in material and energy use
− Strength of the new material reduced if necessary

Need: Efficient manufacturing technologies with high material rates for repair

Figure 10: Efficient manufacturing technology for component repair

Additive manufacturing technologies, such as Laser Metal Fusion (LFM) or Laser Metal Deposition (LDM), can be used for component repair. In these processes, the material, provided as powder or wire, is melted locally on the surface of the component to be repaired using a laser. Any material thickness and geometric elements can thus be created on existing workpieces by applying the material in strips or layers.

Advantages of these processes are the local application on the original component as well as the significant reduction of material and energy input compared to the new production of the component. Disadvantages may be the reduced strength of the added material layers, especially for highly stressed components.

The challenges for the implementation of these technologies within the circular economy lie, among other things, in the limited consistency of the data for the digital twin. These processes must be integrated into existing process chains so that efficient repair of the components is possible. Likewise, the information from the additive process must be integrated into an existing digital twin of the product so that it can be ensured that the functional properties of the component are described with sufficient accuracy after repair.

From the perspective of a manufacturing company, the two production technologies represent an enabler for the development of new business models, in this case repair (R4). In this way, the manufacturing company can open up new markets and at the same time contribute to extending the EOU of the product.

The development of new business models is also the focus of the third example, see Figure 11. Mercedes-Benz carries out remanufacturing of various products for passenger cars or commercial vehicles and then sells these products to the end customer under the label *Mercedes-Benz Genuine Remanufactured Parts* [22]. The example is assigned to the approaches for transparent manufacturing processes and new business models, scenario Remanufacture (R6).

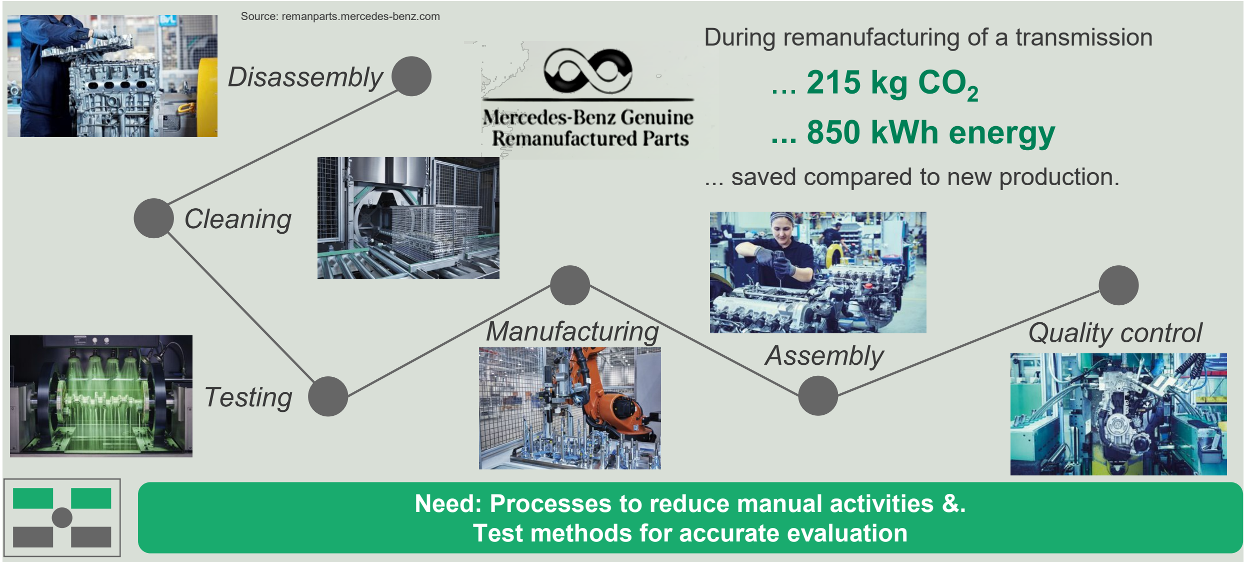


Figure 11: Spare parts made at Mercedes-Benz through remanufacturing [22]

In this process, the products usually pass through a process chain consisting of the following steps:

- Disassembly
- Cleaning
- Components testing
- Manufacturing
- Assembly
- Quality control

Once the process chain has been run through, the products can be installed in the vehicle and are to be regarded as equivalent new parts in terms of service life. In the life cycle assessment, 215 kg of CO_2 and 850 kWh of energy can be saved for the remanufacturing of a transmission compared with new production.

The process described above is currently very much characterized by manual activities. For this reason, the remanufacturing of products is currently only economically viable for very few products. In the future, it must therefore also be possible to automate the required processes for single-item and small-batch production. Concepts with teachable robots in a human-robot collaboration, such as cobots, or advances in AI-supported programming and object recognition could help here. Likewise, new methods are needed that allow non-destructive evaluation of different components for their remaining service life. This could be done, for example, on the basis of the digital twin and the collection of further data from the use phase. However, the meaningful collection of data, the reduction of the amount of data to be stored and the availability of the data for external third parties are issues that have not yet been clarified.

This example illustrates the transition between life cycle and production cycle according to Figure 5. The remanufacturing of existing products results in new requirements for production. Suitable technologies must be identified that allow efficient remanufacturing while ensuring functional properties. In the future, these new business models may therefore lead to innovative new manufacturing technologies.

3.2 Examples and perspectives for the production of sustainable products

In this section, examples and perspectives on the *production of sustainable products* category are addressed. In contrast to section 3.1 the following three examples are not oriented to the sustainability approaches of actual manufacturing but focus on the rapid availability of innovative and, above all, sustainable products. In this context, the aspects from the approaches and in particular from the prerequisites for a digital twin in manufacturing come to the fore.

The first example addresses the development of so-called high bypass ratio (HBR) engines to reduce fuel consumption and noise emissions of commercial aircraft engines (see Figure 12). For research purposes of the German Aerospace Center (DLR), the Fraunhofer IPT manufactured a 1:3 scale integral titanium fan for the purpose of testing crosswind effects on a special engine test rig. Following the product design, the main process steps included computer-aided pro-cess design, turning and milling, and final quality assurance.

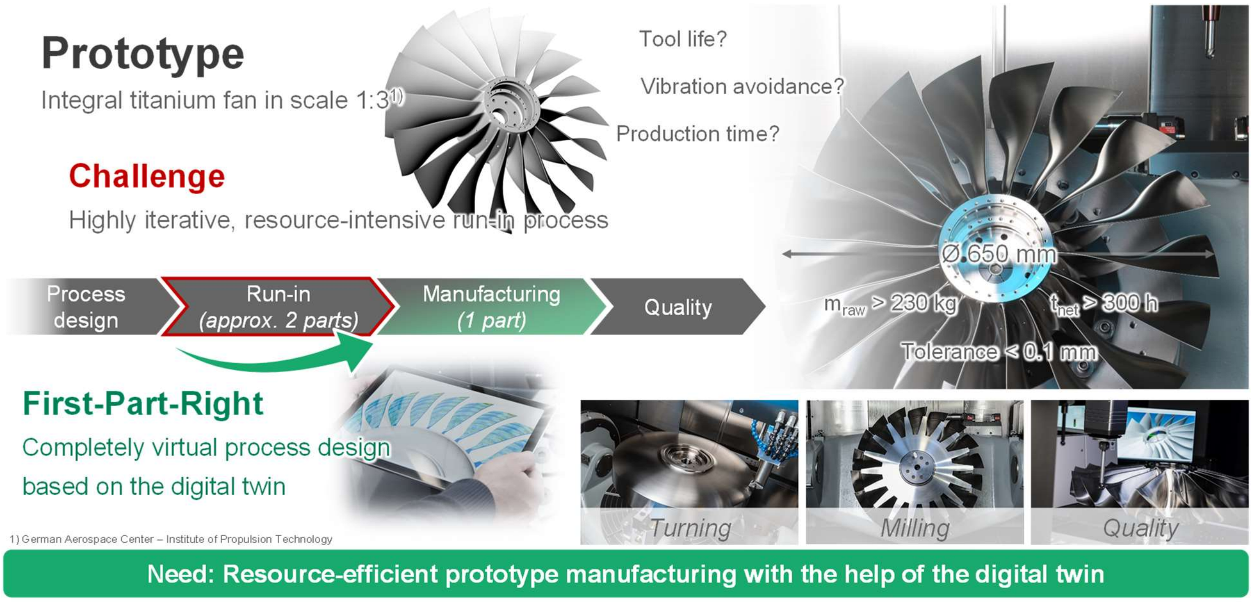


Figure 12: Resource-efficient prototype manufacturing for low-emission aviation engines

The industrial state of the art to produce such aero engine components is characterized by an experience-based process design and highly iterative, resource-intensive run-in procedures. In contrast, the computer-aided process design at the Fraunhofer IPT was carried out completely virtually based on the digital twin. The focus here was on determining stable spindle speeds, estimating the tool life and maintaining permissible geometric deviations of the flow surfaces. The required simulation tools mainly comprised numerical and analytical models, which were integrated with the computer-aided design and manufacturing (CAD/CAM) environment via appropriate interfaces. In this way, the prototype could be manufactured resource- and cost-efficiently according to the *first-part-right* principle. It was possible to completely dispense with the normally required run-in and reserve components and the associated scrap.

The digital twin was also used profitably in the actual production of the prototype. The focus here was on the high-frequency acquisition of machine and sensor data from the machine tool and the resulting determination of component quality and resource consumption. For this purpose, an edge cloud-based data acquisition and processing solution was used, which calculated the geometric deviations of the component as well as the total energy consumption and other sustainability parameters from the acquired raw data. In this way, data-based quality assurance was realized based on the digital twin and a significant contribution was made to a precise life cycle assessment (LCA).

In the example shown, the digital twin supported the economic and resource-efficient production of the prototype as well as compliance with the high tolerance requirements. A key differentiator compared to the industrial state of the art was the use of extensive technology models for simulation and data processing. In addition to further research and development of the required Internet-of-Things (IoT) infrastructure, the further exploitation of these models represents a key success criterion for the industrialization of the digital twin.

Another example of the use of the digital twin in the design of sustainable product production is shown in Figure 13. In this example, we are dealing with the digital ramp-up process, which, analogous to the production of the blisk, is based on the increase in the analysis and forecasting capability through the digital twin.

The ramp-up process for a series production usually represents a personnel and time-consuming process for manufacturing companies. Extensive experimental investigations on small and medium batch sizes are necessary in order to adjust the manufacturing processes and the manufacturing sequences within the process chain. Between these investigations, regular adjustments of the process parameters up to design changes of tools and clamping systems take place in order to ensure the desired quality and cycle time of the product. This process currently often takes place heuristically on the basis of empirical knowledge or with the aid of process simulations. As product development cycles become shorter and shorter, e.g. for new wind turbines or fuel cells, a more flexible alignment of production and manufacturing chains will become increasingly important in the future. Therefore, there is great potential in a digitally supported ramp-up process. Here, the digital twin is used to accelerate the ramp-up process on the basis of additional data (sensors for e.g. temperature and force, material data) and to reduce the necessary iteration loops through analytical data models. The aim is to use the digital twin to obtain an automatable prediction of the process parameters, which will enable stable process control in compliance with the product requirements.

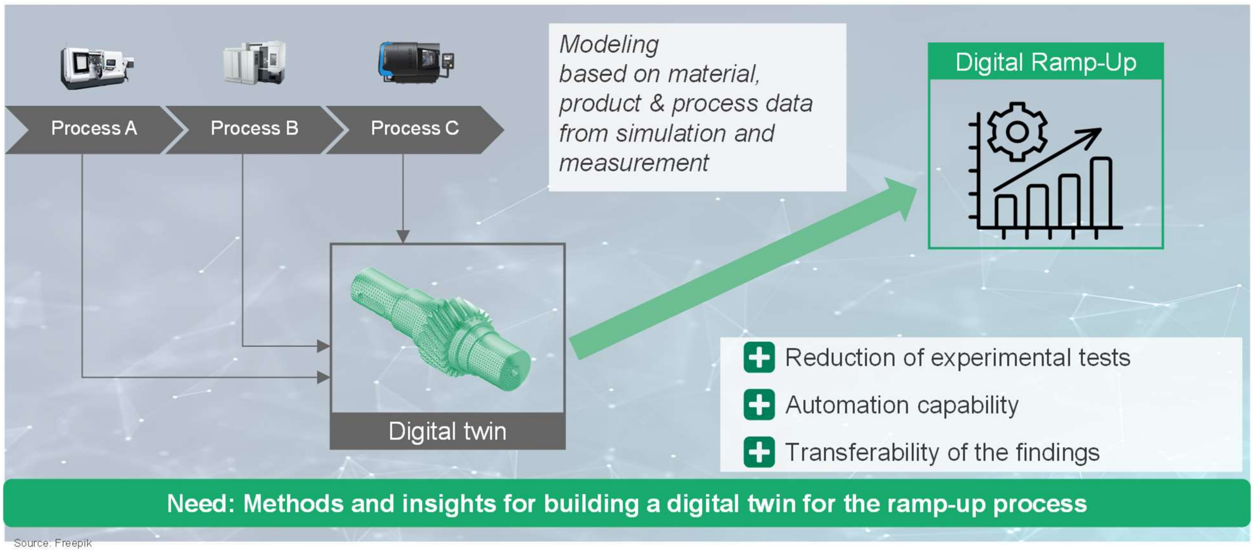


Figure 13: Digital ramp-up process for efficient manufacturing of the future

This method is currently being used in the research environment for an industrial ramp-up process for an application in the field of forming (roll bonding). When setting up a new production line, additional sensors are installed in the machines to measure various process parameters. These recorded process data are combined with the incoming material data (e.g. sheet thickness) in a digital twin of the sheet. By analyzing the process data, the material data and the generated part quality, correlations between the different parameters can be determined and used to control the process via corresponding models. This can create a model-based automation of the start-up process for roll bonding. The findings can then be transferred to series operation and used there for process control.

In addition to the creation of the digital twin, the main challenge here is the methodical structuring of the digital ramp-up process. It is necessary to find out which sensors and measurable parameters are required to determine correlations between component quality and process control, see approaches to functionally relevant properties. Likewise, methods must be created which allow multi-objective optimization of the process chain. In this context, it is also necessary to resolve the conflicting goals of product function, costs and sustainability. If the implementation is successful, the next step is to automate it in the best possible way.

Another example of new innovative sustainable products is shown in Figure 14. In the example given here, it is a functionally integrated development and production of a hydrogen-powered gas turbine.

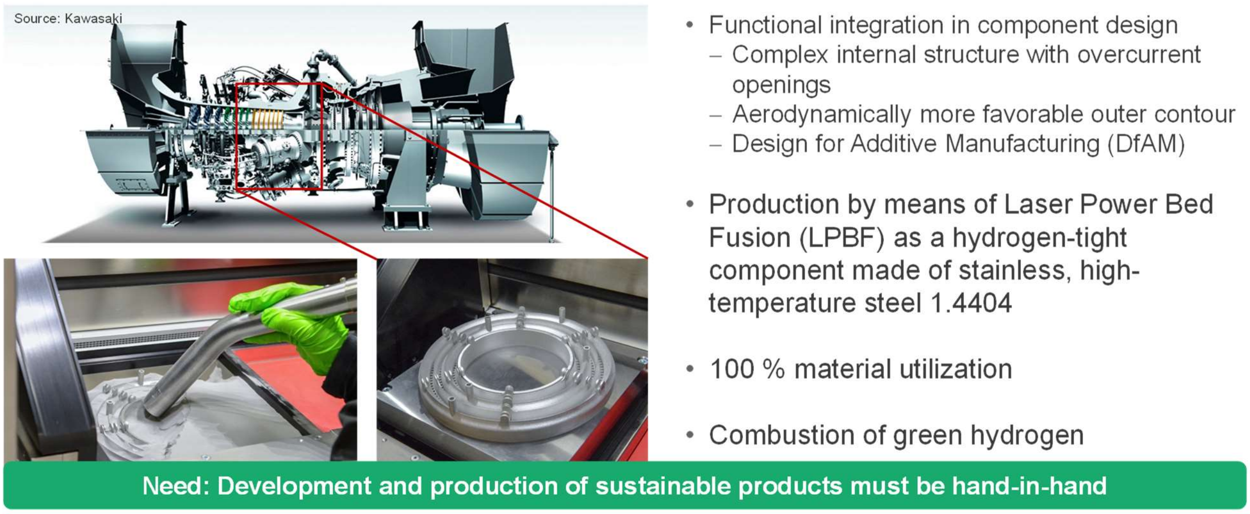


Figure 14: Function-integrated development and production of sustainable products

For this purpose, a combustion chamber for the combustion of hydrogen for energy generation was developed at the Fraunhofer IPT together with Kawasaki company. The requirements for the combustion chamber and the functions necessary for this were taken into account directly in the component design in interaction with the manufacturability. Thus, using the familiar approach with Design for Additive Manufacturing (DfAM), it was possible to realize a function-optimized inner and outer structure of the component for the LPBF process. This made it possible to achieve 100 % material utilization for the component.

The further merging of development and production is to be seen as a need for the future here. Particularly for the manufacture of such innovative and above all sustainable products, the consideration of production and especially also upgradeability and reprocessing in the development phase is of immanent importance. Without a suitable product design, suitable manufacturing technologies for extending the service life can often only be used uneconomically.

3.3 Vision

The vision for a marketplace for secondary parts in the form of semi-finished products is shown in Figure 15. Here, the product value of any technical product is to be maintained as best as possible or, if necessary, increased. This can be done within an existing product life cycle but also outside the company in another, new product life cycle. In particular, the reuse of subcomponents as semi-finished products for new products represents a significant factor for increasing the sustainability of the industry due to economies of scale. For example, energy-intensive heat treatment routes for the production of as-new semi-finished products can be substituted. In particular, the availability of the relevant condition data of the semi-finished products via the digital twin will be an essential prerequisite.

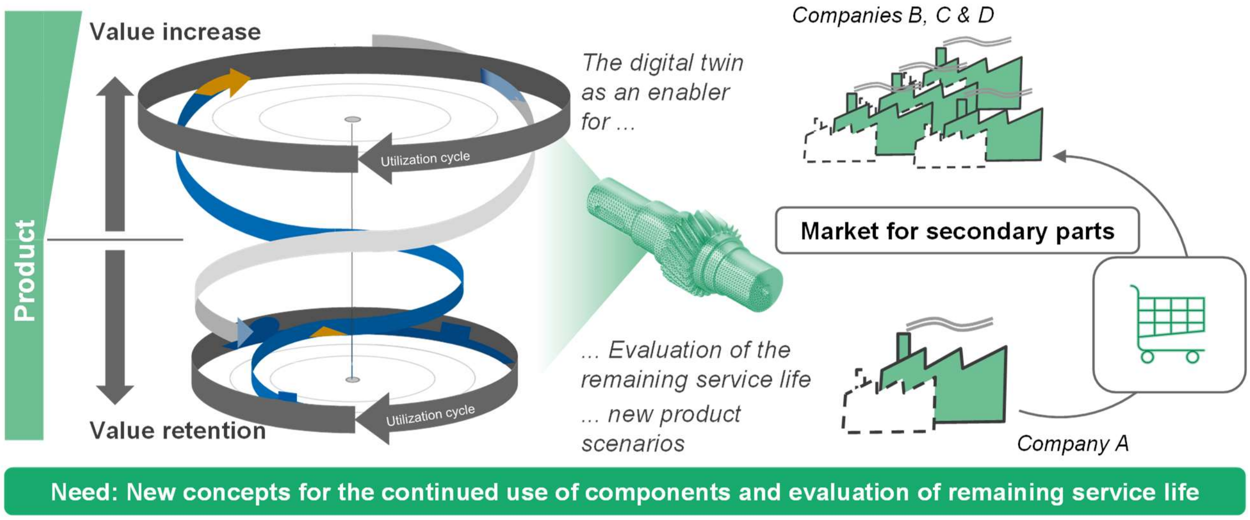


Figure 15: Semi-finished products as starting material for sustainable new products

To enable the reuse of subcomponents, for example, a marketplace (platform) must be created to make these components available, see figure on the right. The digital twin of the subcomponent is a key enabler for this marketplace. This is because knowledge of the remaining service life or the loads during the life cycle is important for the sensible use of subcomponents or semi-finished products. Especially for highly loaded components, such as gears, drive shafts or bearings, the information about the fatigue state of the material must be known. Based on this condition description, a decision can be made about further use as a semi-finished product for new products. It would also be conceivable to classify the semi-finished products on the basis of the intended use. For example, the requirements of the semi-finished products for lower future loads would be lower, so that a larger quantity of semi-finished products can be considered.

This marketplace requires the existence of models for estimating the fatigue state of the material or the remaining service life. Initial approaches for estimating remaining service life already exist in the literature. However, these approaches are very specialized to certain types of components. Approaches that allow a more general formulation of remaining service life are therefore to be explored in the future. Likewise, measurement methods for material characterization must be further developed so that an estimate of the damage state of the material can be obtained, if possible non-destructively. Third, the digital twin for a component must be structured in such a way that only the data necessary for evaluating the remaining service life along the component's life cycle and the current geometric shape are stored. Should these approaches become available in the future, a new industry could be opened up, which would open up the secondary market for subcomponents and massively increase the sustainability of our industry.

4 Summary

Increasing the sustainability of our products and our industry represents the goal for the coming years and decades. The literature shows that the circular economy, and in particular the implementation of the R-scenarios, provide methods and techniques to achieve this goal. Four approaches have been identified for manufacturing companies to successfully implement sustainability. From the point of view of manufacturing companies, there are essentially two fields of activity that are oriented to the four approaches. One is the creation of sustainable products. The second is the production of sustainable products. The digital twin is an important enabler for the successful implementation of these two fields of activity. Only with the availability of product-specific data can decisions be made and analyses carried out that will lead us to more sustainable production and the production of sustainable products.

The fields of activity have a number of challenges in common which make current implementation difficult. Examples include the frequent lack of digitization and availability of the digital twin, the high economic investment required, the lack of customer acceptance for refurbished or reused products, and the lack of regulatory framework conditions.

In this presentation, different examples from the two fields of activity are given. For the examples, it becomes clear that science must develop new and better models to determine the remaining service life of components in the future. Likewise, it becomes clear that the availability of the digital twin must be significantly increased. On the other hand, new manufacturing technologies and production processes must be developed that enable efficient processing of individual and small series. Likewise, new product innovations must be focused on which, through a direct coupling of development, production and use, design products that already contain a value retention or value increase strategy after the initial service life has been reached.

Close discourse between research and industry is therefore very important for the coming years and decades. Only in this way can we address the numerous challenges and find and implement solutions.

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2.2 Energy and Resource Efficiency in Manufacturing

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Abstract

Energy and Resource Efficiency in Manufacturing

The compatibility of economic and ecological sustainability is increasingly determining the strategies of manufacturing companies. The focus of ecological sustainability is primarily on energy and material efficiency in the company's own production. However, many possibilities that could already be used in the company's own production to reduce energy consumption and increase material efficiency remain unused. In the medium to long term, for an economy in a sustainable society, moreover, cross-company activities will increasingly have to be initiated and become effective. This requires close, product-specific cooperation from all participants along the respective value chains as well as the development and implementation of new sustainability approaches. Therefore, this paper presents current best practices for increasing energy and material efficiency in manufacturing. With a view to the potentials of tomorrow as well as the future challenges, promising possibilities and examples for realising the urgently needed circular economy will continue to be highlighted, taking into account different R-cycles based on the digital twin of product and manufacturing.

Keywords: energy, resources, manufacturing, efficiency, product lifecycle

Kurzfassung

Energie- und Ressourceneffizienz in der Fertigung

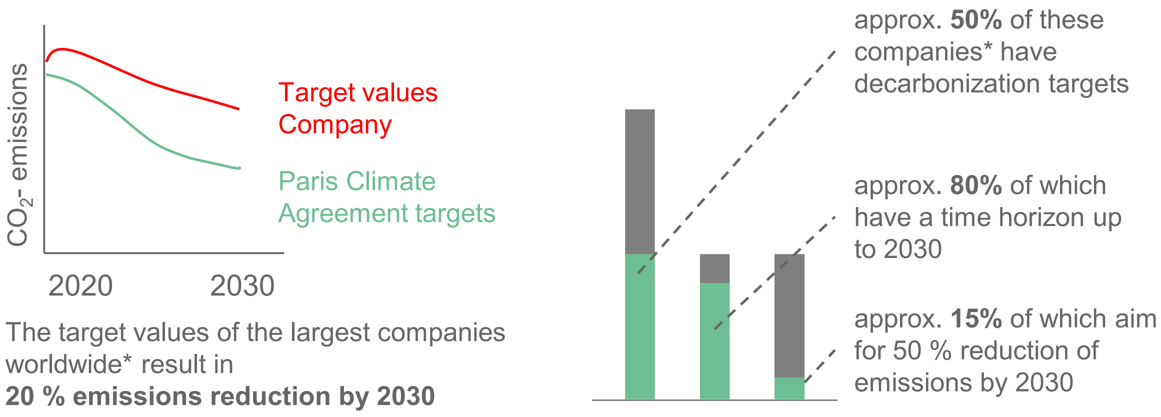
Die Vereinbarkeit von ökonomischer und ökologischer Nachhaltigkeit bestimmt zunehmend die Strategien fertigender Unternehmen. Im Fokus der ökologischen Nachhaltigkeit stehen vor allem die Energie- sowie die Materialeffizienz in der eigenen Produktion. Viele Möglichkeiten zur Senkung des Energiebedarfs und zur Erhöhung der Materialeffizienz in der eigenen Fertigung bleiben jedoch bisher ungenutzt. Unternehmen, die hier bereits die Initiative ergriffen haben, konnten bereits kurzfristig Potentiale zur Energieeinsparung heben und Wertstoffe und Materialien erstmals in Wertstoffkreisläufen führen. Mittel- bis langfristig werden für eine Wirtschaft in einer nachhaltigen Gesellschaft darüber hinaus zunehmend unternehmensübergreifende Aktivitäten initiiert und wirksam werden müssen. Dies erfordert eine enge, produktspezifische Kooperation von allen Beteiligten entlang der jeweiligen Wertschöpfungsketten sowie die Entwicklung und schnelle Umsetzung neuer und innovativer Nachhaltigkeitsansätze. Daher wurden im vorliegenden Beitrag aktuelle Best-Practices zur Steigerung der Energie- und Materialeffizienz in der Fertigung vorgestellt, die in enger Diskussion mit OEMs, Komponenten- und Maschinenherstellern, Betriebsmittellieferanten sowie Herstellern von Sensor- und Monitoringsystemen identifiziert wurden. Mit einem Blick auf die Potentiale aber auch Herausforderungen von Morgen sowie die zukünftigen Herausforderungen werden weiterhin vielversprechende Möglichkeiten und Beispiele zur Realisierung der dringend benötigten Kreislaufwirtschaft unter Berücksichtigung unterschiedlicher R-Szenarien auf Basis des Digitalen Zwillings von Produkt und Fertigung beleuchtet.

Schlagwörter: Energie, Ressourcen, Fertigung, Effizienz, Produktlebenszyklus

1 Motivation and current challenges

Hardly any other topic has moved society and industry as much in recent years as the issue of sustainability. Both socially and politically, there is a growing desire to take effective measures to protect our environment. The industry plays a key role in this. In 2021, the entire german industrial sector was the second largest emitter of greenhouse gases after the energy industry (247 million tons of CO_2 -eq), with 181 million tons of CO_2 -eq [1]. This brings industry into focus in the search for **potential savings**, which are more and more being pushed by business and politics.

Based on a growing number of climate protection laws, such as the Paris Climate Agreement and the German Climate Protection Act, manufacturing companies are also increasingly required to reduce their greenhouse gas emissions and use renewable energies as the basis for their operations. According to the Paris Climate Agreement targets, greenhouse gas emissions are to be reduced by 43% by 2030 and 84% by 2040 compared to 2019 levels [2]. Nevertheless, analyses by the consultancy Roland Berger have shown that so far only around 10-15% of all large companies have committed to aiming for an overall emissions reduction of 50% by 2030. On the contrary, calculations show that if all the target values of the largest listed companies in the most important industrialized countries are added together, the result is a reduction in CO_2 emissions of only 20% by 2030, as shown in Figure 1. [3] This is significantly below the required 43%. Each company must therefore increase its efforts in order to still achieve the Paris climate target. Roland Berger also notes that only 50% of large companies worldwide currently have **decarbonization targets**. The scope of the study was based on the 4,700 companies with the largest market capitalization, the 166 largest CO_2 emitters and the 2,000 largest listed companies worldwide by revenue. However, only 80% of these have decarbonization targets within the 2030 time horizon, with 15% of companies having targets for 50% emissions reductions by 2030.[3] In summary, companies will have to cut CO_2 much more consistently in the future than they have so far if the Paris climate targets are to be met.



*Based on the 4,700 companies with the largest market capitalization, the 166 largest CO_2-emitters and the 2,000 largest listed companies worldwide by revenue

Figure 1: Target emissions reductions by large companies are insufficient to meet the goals of the Paris climate agreement [3]

In Germany, anchored in the German Commercial Code (HGB), large capital market-oriented companies as well as credit institutions and insurance companies with more than 500 employees are also required to publish sustainability reports that report on the company's ecological and social impact. The report must contain information on environmental, social and labor issues as well as respect for human rights and anti-corruption measures. The reporting obligation has been in force in Germany since the 2017 fiscal year and was expanded in 2021 as part of a reform of the German Commercial Code. Companies must disclose their resource and energy consumption as well as their greenhouse gas emissions and their strategies for reducing these factors. In addition, strategies for **adapting to climate change, energy efficiency measures and recycling activities** must be presented, and the supply chain and its interaction with the company's own sustainability goals must be demonstrated. [4]

In this context, companies face the difficulty of collecting and providing all the necessary data and information for comprehensive reporting. Small and medium-sized companies in particular often have limited resources and expertise in this area. The increasing pressure towards reporting and ultimately towards sustainability is additionally flanked in many industries by customers in both B2B and B2C business. In the automotive industry for example, ESG (Environment, Social and Governance) ratings are increasingly mandatory for suppliers. OEMs are increasingly demanding sustainability reports from their suppliers, as typically over 90% of the emissions in the sustainability balance sheet of OEMs are Scope 3 emissions (see Figure 2). Investors and customers are also increasingly relying on ESG information to inform decisions and strengthen their commitment to sustainable companies. Thus, there is a competitive advantage for suppliers that publish ESG information on a voluntary basis, respond to their customers' ESG requirements, and thereby present themselves more transparently to their stakeholders. [5]

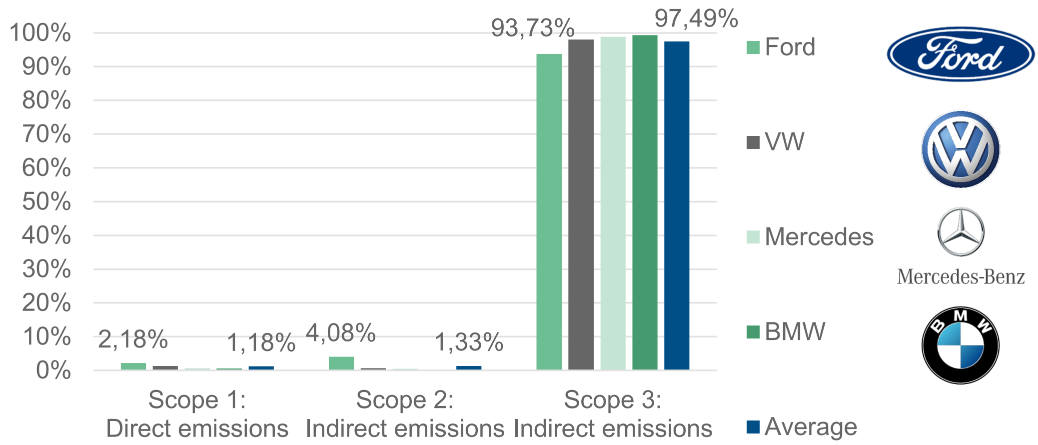


Figure 2: More than 90% of the emissions of automobile manufacturers are Scope 3 emissions [6]

Scope 1, 2 and 3 emissions are categories defined by the Greenhouse Gas Protocol Initiative to classify and measure greenhouse gas emissions from companies. Scope 1 emissions are direct greenhouse gas emissions resulting from the combustion of fossil fuels or from processes within the company, e.g. emissions from heating systems or machinery. Scope 2 emissions are indirect greenhouse gas emissions that result from the purchase of electricity, steam or refrigeration, for example. Scope 3 emissions are all other indirect emissions that arise from the activities of companies but are outside the boundaries of the company. This includes emissions resulting from the production of raw materials, the production of (pre-)products, the use of products by customers, the disposal of waste products, and the use of transportation, i.e. indirect greenhouse gas emissions along the upstream as well as downstream supply chain. This also includes the activities of any suppliers. As OEMs are affected by the sustainability reporting obligation, they accordingly require sustainability data from their suppliers and are increasingly making the provision of this a condition of a business relationship.

Manufacturing companies face the challenge of meeting ecological sustainability requirements without losing sight of economic aspects. Due to the **high product and plant diversity,** there is no patent recipe for implementing sustainability in manufacturing companies, which often leads to an unsteady entry into the topic of sustainability accounting and improvement. For this article, therefore, **current best-practice approaches** for short-term implementation in the company were developed together with practicing companies. Furthermore, a clear framework for the cross-life cycle consideration of the sustainability of manufactured products is introduced. Finally, an outlook on future opportunities and challenges on the way to a more sustainable manufacturing is given.

2 Manufacturing as an enabler for increasing environmental product sustainability

Where the relevant levers for increasing sustainability and realizing savings potential lie is company-specific and highly dependent on the product.

A distinction can be made between the extent to which environmental impacts occur during production or in the use phase of the product. This can be demonstrated by the three examples of products illustrated in Figure 3.

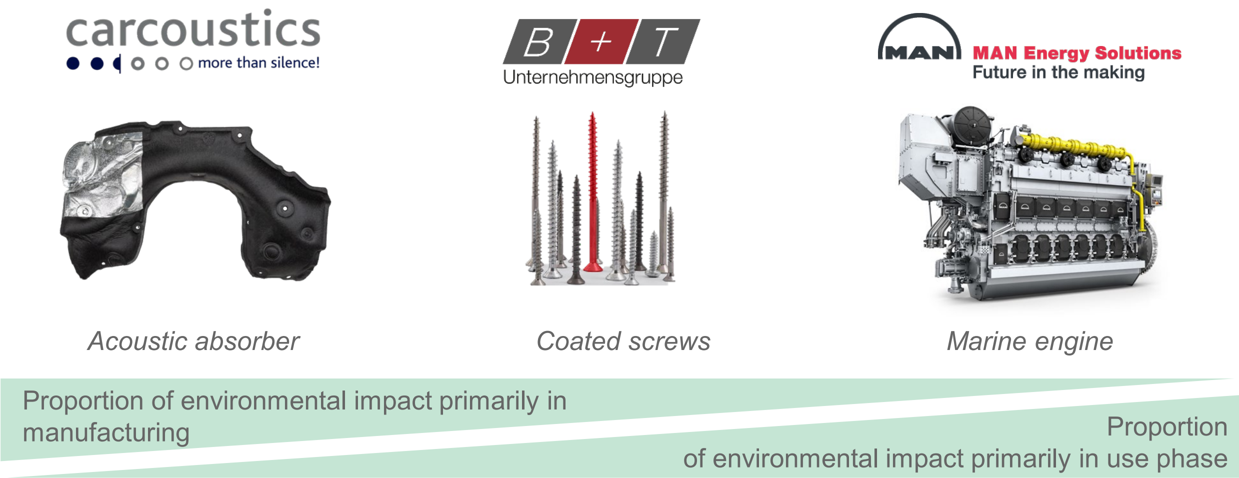


Figure 3: Individual environmental impacts illustrated using example products from the expert group

The Carcoustics acoustic absorber for the automotive sector is made of plastic and consumes energy and material during production. In the use phase itself, it does not actively cause emissions, nor does it have any influence on the service life of the car. Only through its weight does the absorber influence the level of CO_2 emissions of the car. Depending on the design of the absorber, however, the difference in weight is only a few grams, which is negligible against the background of the total CO_2 emissions of a car in the use phase. The second product, a coated screw from the B+T Group, was galvanized, which initially means increased environmental impact in production compared with a non-galvanized screw. Due to the coating, the end product held together with the help of the screw potentially lasts longer than when using screws without a coating. The life of the screw often has a direct impact on the life of the end product, as the end user may replace the product when the screw is loosened. Therefore, if the use of the galvanized screws results in fewer new end products having to be produced, all associated emissions are saved. In the overall balance, the increased use of resources in the production of the screw due to electroplating can be outweighed by the savings over the extended product life cycle. Products such as the illustrated marine engine of the company MAN Energy Solutions in figure 3, on the other hand, generate a large part of their environmental impact during the use phase. The marine engine shown, for example, generates less than 10 t CO_2 per engine during its own production, but in the life phase, depending on the load profile, emissions amount to several 10,000 t/a CO_2 with an operating phase of often well over 20 years.

For the sake of the environment, the goal for manufacturing companies must be to minimize the overall environmental impact, regardless of the life cycle phase in which it is caused. The individual levers that can be used to achieve particularly large effects are product-specific. In the case of the acoustic absorber shown, the direct levers lie primarily in production, while in the opposite case of the marine engine, they lie in the utilization phase. However, the potential for increasing service life and efficiency in the utilization phase can also be realized decisively with measures taken during production. The effect of the coated screw depends primarily on the application and the environmental conditions to which the screwed end product is exposed.

To enable the identification and realization of significant levers to increase the sustainability of products and their manufacturing, a four-step **systematic framework** (see Figure 4) can be used. The first step is to define the target of the measures, the so-called balance limit, within which measures to increase sustainability are to be taken. At best, this should be uniformly defined for the entire value chain so that the environmental impacts at different points in the life cycle phases can be compared. Also, in order to be able to make an overall statement about the sustainability of a product, the various partners in the value chain must quantify sustainability in the same way (see Section 3). Currently, however, these balance limits are often still defined on a company-specific basis. Anyway this makes it possible to quickly identify the levers for increasing sustainability and quantify their effects for the company's own manufacturing processes (see section 4).

In order to be able to evaluate the achievement of objectives, environmental sustainability must first be quantifiable. "***You can't manage what you don't measure"*** is an apt quote from the US economist Peter Drucker. Improving ecological sustainability and meeting targets precisely is not possible if the actual ecological sustainability can not be quantified. To make it quantifiable, the relevant variables in production must be made measurable on the one hand, and a method must be used on the other hand that translates the measured numerical values into a statement about the effect of measures to increase ecological sustainability. With the aid of so-called life cycle assessment, methods are given which convert the variables measured in the company into, for example, a CO_2 equivalent and thus make them comparable. However, the result depends on which data are taken into account in the balance limits and how good the quality of these data is. The "right" data must therefore be collected. When the company's environmental sustainability can be measured, the existing deficits can be identified. From the deficits and potentials, targeted measures can be derived with the help of which production can act in a more resource-conserving and energy-saving manner. These measures are manifold. On the one hand, there are short-term individual measures IN production. Although these have a limited effect, they can be implemented quickly and can be very effective, especially when taken together. These short-term measures are located directly IN manufacturing, e.g.

using standby modes and switching to green power. However, as noted above, the entire product lifecycle is relevant to the holistic sustainability view. Often, the levers that lie in the product use phase are the greatest, as they affect longterm consumption and associated emissions. The associated measures that exist WITH manufacturing (e.g. the manufacturing process-related efficiency increase of an engine) are long-term and can mean that more resources should also be used once in manufacturing if the savings from this outweigh the costs over the entire product life cycle. Production therefore has a dual role to play. On the one hand, it is important in the short term to seize potential for increasing internal sustainability, while in the medium to long term manufacturing is increasingly assuming the important role of an enabler for sustainable products (see Figure 4).

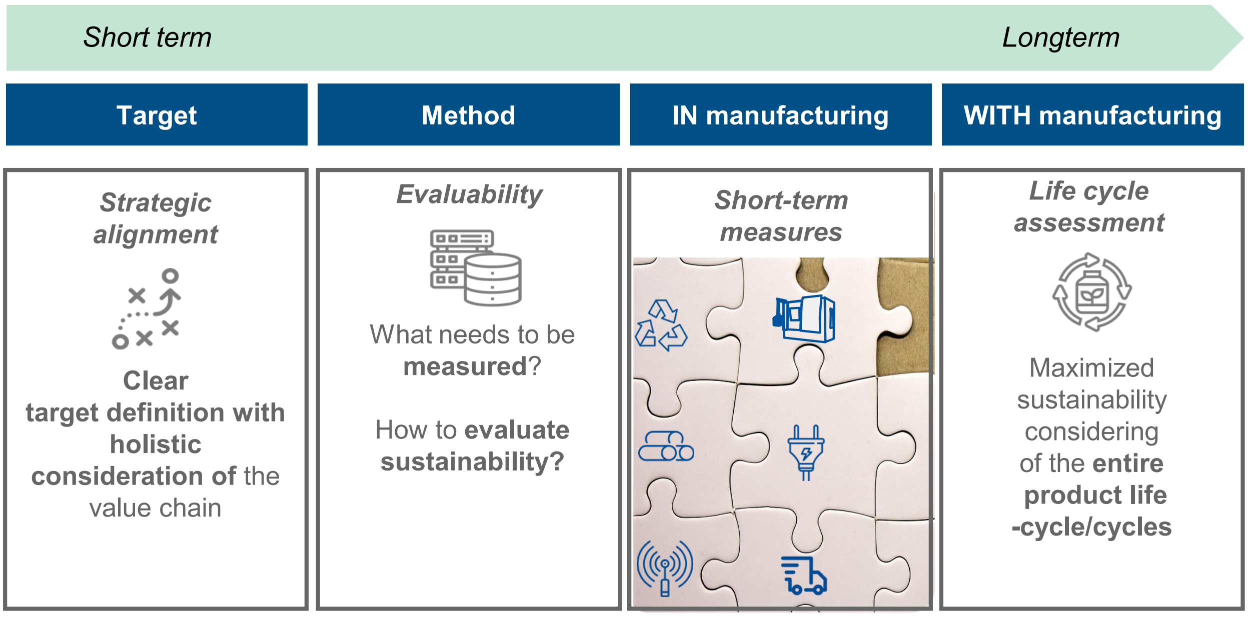


Figure 4: Procedure for identifying levers to improve sustainability

3 *"You can't manage what you don't measure"* - Basics of Life Cycle Assessment

In order to be able to improve the ecological sustainability of one's own manufacturing and the manufactured products, one must first be able to quantify it. There are various methods that can be used to assess the ecological impact of companies and manufacturing processes (see Figure 5). The basis of all listed methods is **life cycle assessment** according to DIN EN ISO 14040/44. Life cycle assessment offers the possibility to consider all impacts of a product, process or service on the environment from raw material extraction to disposal. Thus, LCA can be performed either for a single product, a manufacturing process or for the entire company. [7], [8]

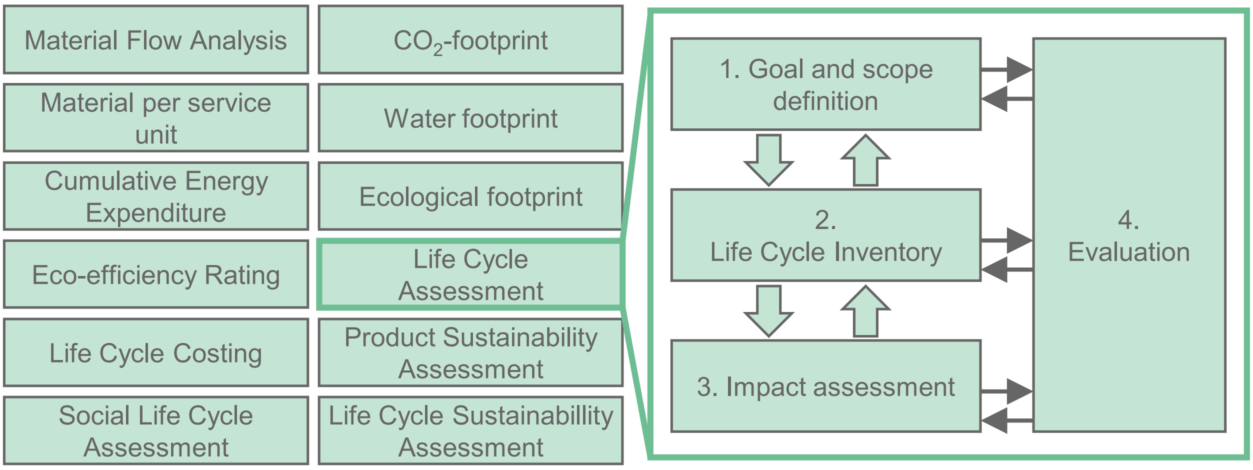


Figure 5: Collection of methods for ecological assessment according to Andes [9] and the four phases of a life cycle assessment according to DIN EN ISO 14040 [7]

Life cycle assessment consists of four distinct phases, which are iterated through. The four phases are:

1. **Goal and scope definition:** In this phase, the object of investigation to be analyzed is defined. This includes the definition of the functional unit, the system boundaries, the data sources and the methodological approaches (see Goal/Scope section 2).
2. **Life cycle inventory:** In this phase, data on the environmental impacts of the product or service are collected and analyzed. For this purpose, various tools, methods and models are usually used to quantify the environmental impacts in the different phases of the life cycle.
3. **Impact assessment:** In this phase, the identified environmental impacts on the environment and human health are assessed. For this purpose, the impacts on different categories such as climate change, acidification, eutrophication, resource use and toxicity are quantified.
4. **Evaluation:** In this phase, the results of the life cycle assessment are interpreted and communicated. This involves evaluating the results in relation to the objectives and contexts of the study and presenting the results to support decisions to reduce environmental impacts.

In the following, the phases of the life cycle assessment are explained using the example of the production of a pinion shaft. In a research demonstrator at the WZL | RWTH Aachen University, a pinion shaft was manufactured for an electric drive of a passenger car. A life cycle assessment was carried out for the production of the pinion shaft. The aim of the LCA was to calculate the environmental impacts of the manufacturing processes. In this so-called gate-to-gate approach, all value-adding steps in the production process are taken into account, see Figure 6. The use as well as the disposal of the pinion shaft were not considered in the balance. A total of five manufacturing processes were used to pro-duce the pinion shaft from a round material blank: Soft machining in a turning-milling center, soft gear cutting, hardening, grinding (cylindrical grinding), and hard gear cutting (profile grinding). It should be noted that hardening was performed at an external supplier and thus no data was available for evaluation. Therefore there are four manufacturing processes form the product system considered for the LCA. The functional unit of this product system is the manufacturing of a pinion shaft. The functional unit of a product system is a reference unit to which all environmental impacts are related.

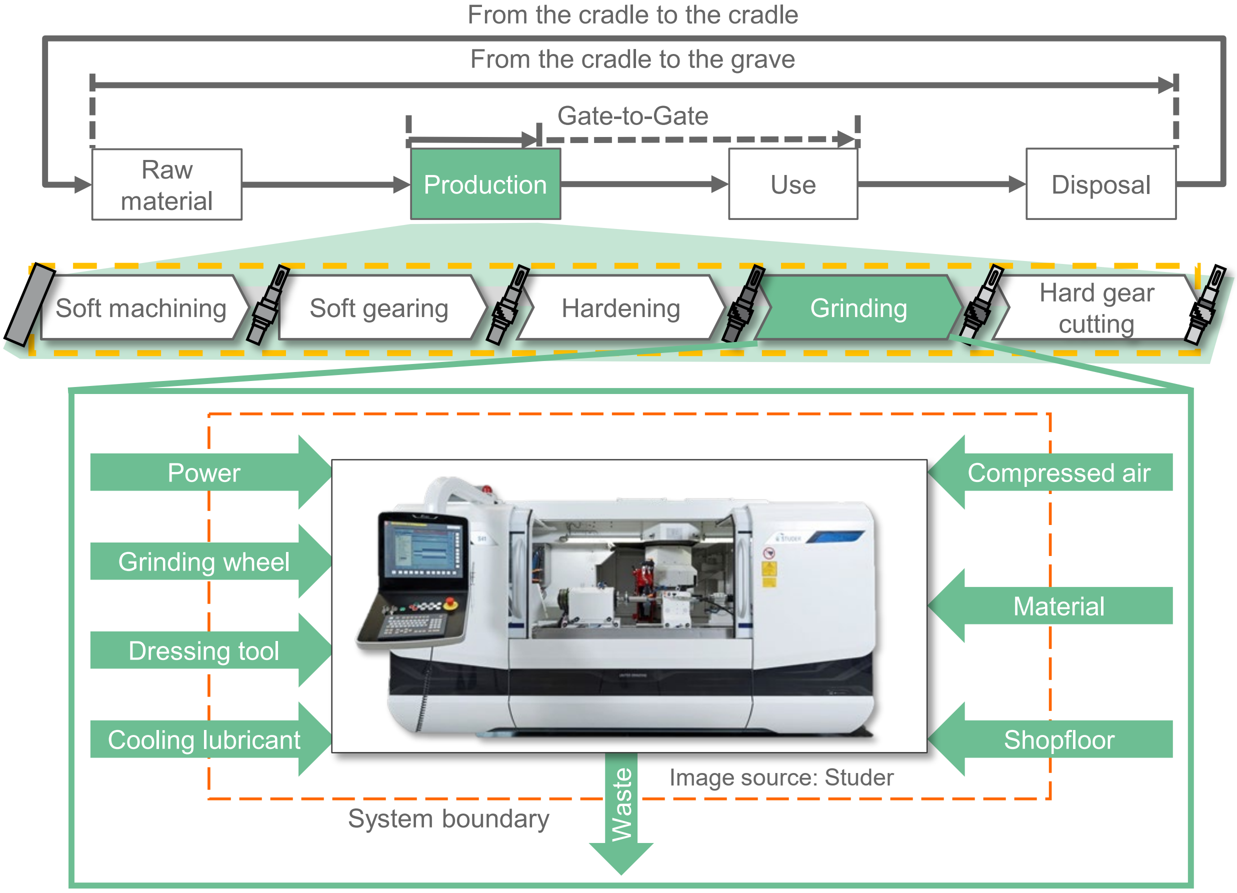


Figure 6: Product system for manufacturing the pinion shaft and currents to be balanced in a manufacturing process using the example of a grinding process

The second phase of the LCA is the life cycle inventory. In the life cycle inventory, all relevant energy and material flows for the individual production steps are identified and recorded. Ultimately, environmental impacts arise exclusively from the use of energy in the form of electricity, heat, cold and chemical processes, and from the use of materials. Each material finds its origin in the environment where raw materials are mined and further processed through the use of energy. Energy is provided in the form of electricity by power plants, and the environmental impact depends on the electricity mix of the country, region or company.

Figure 6 shows the life cycle inventory for the cylindrical grinding process in qualitative terms. These energy and material flows were recorded for the LCA. Sensors were retrofitted to record the electricity consumption.

In the third phase of the LCA (impact assessment), the ReCiPe method was used to calculate the environmental impacts [10]. This is a renowned method, which is widely used in the scientific literature. ReCiPe can be used to calculate up to 16 different environmental impacts, such as climate change, water consumption, particulate matter pollution, and soil or ocean acidification. The impact assessment methods are multi-interdisciplinary projects in which a large number of research groups in their respective fields describe and quantify the environmental impact of individual substances on the environment. The methods are a current subject of research and are regularly updated.

Figure 7 shows an evaluation of the life cycle assessment. The diagram shows the emitted CO_2 -eq per manufactured pinion shaft. On the top, only the manufacturing processes were taken into account. On the bottom, the CO_2 backpack of the processed semi-finished product was also taken into account. It is noticeable that the raw material already contains a great deal of CO_2 of the end product. It is therefore particularly important to use resources IN manufacturing efficiently and to avoid rejects. It should also be noted that even though the contribution of manufacturing to climate change in this example appears small at first glance, only the emissions of one pinion shaft were considered in this study. In an industrial environment, much higher quantities are produced, and the environmental impacts scale accordingly. The complete study can be found in BECKERS et. al. [11]

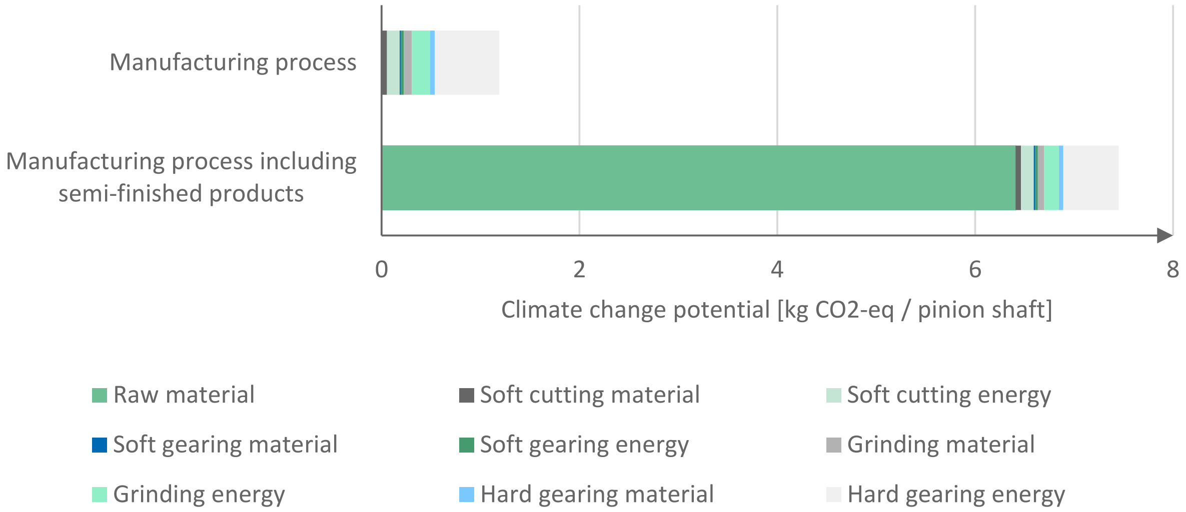


Figure 7: Climate change potential of a pinion shaft with and without consideration of the processed semi-finished product

It should be noted that the expansion of the scope of consideration to include raw material production has greatly increased the environmental impacts. In order to calculate a complete Product Carbon Footprint (PCF), consideration of the use phase and disposal is also necessary. Even though these life cycle phases are often not yet within the balance limit of manufacturing companies, great potentials lie in the right measures WITH manufacturing. Here, for example functional improvements to the pinion shaft can improve the efficiency of the transmission and thus save significant emissions in the use phase of the passenger car. However, in order to take the use phase or the disposal of products into account as early as in the manufacturing stage, a large amount of data from the use phase is required, which must first be collected. Secondly, the value chain must be networked in order to share this data. In order to reduce the PCF, it will be necessary in the future for the stakeholders along the value chain to cooperate more closely.

4 Best practice - examples for increasing efficiency in manufacturing

4.1 Production process-related creation of transparency and derivation of short term measures

The increasing need to create transparency in the use of energy and materials goes hand in hand with the increasing digitalization of processes. Many manufacturing companies are still facing challenges here. For example, energy consumption is often not recorded per machine, but across the entire shopfloor. Data collection should be structured and targeted, i.e. the data must be obtained in the correct granularity for further use. In the example of energy consumption per machine, an electricity meter infrastructure would be necessary on machine level. Current successful approaches in practice have in common the creation of transparency over the production processes and the identification of deviations between target and actual energy and material consumption as well as the associated data-based measures.

The B+T Unternehmensgruppe, for example, has been able to implement such measures by **creating transparency** over its production processes. The associated creation of transparency can take place at various levels. The energy consumption of individual processes in the plants was made transparent for employees with the help of dashboards. Among other things, the energy consumption of electroplating equipment was evaluated in relation to the coated surface. This made it possible to increase the reaction speed, identify deviations between target and actual energy consumption in coating processes, and take measures to increase energy efficiency (see Figure 8). The recorded data revealed significant fluctuations in coated area per energy input in the form of energy consumption peaks that had previously gone unnoticed. In the course of creating transparency, they were uncovered and the causes were researched and improvement measures identified. On the one hand, the targeted visualization of the data, which is adapted to the stakeholder, enables this rapid elimination of unwanted process deviations; on the other hand, it also offers the potential to save energy costs through adjusted production planning and to create transparency for the customer with regard to his orders. With the help of various other measures, such as the adjustment of maintenance cycles, the B+T Unternehmensgruppe was able to reduce energy consumption per unit of coated area produced. In addition, the created transparency enabled strategic decisions to be made on shifting the timing of processes with high energy consumption to times with relatively low electricity costs.

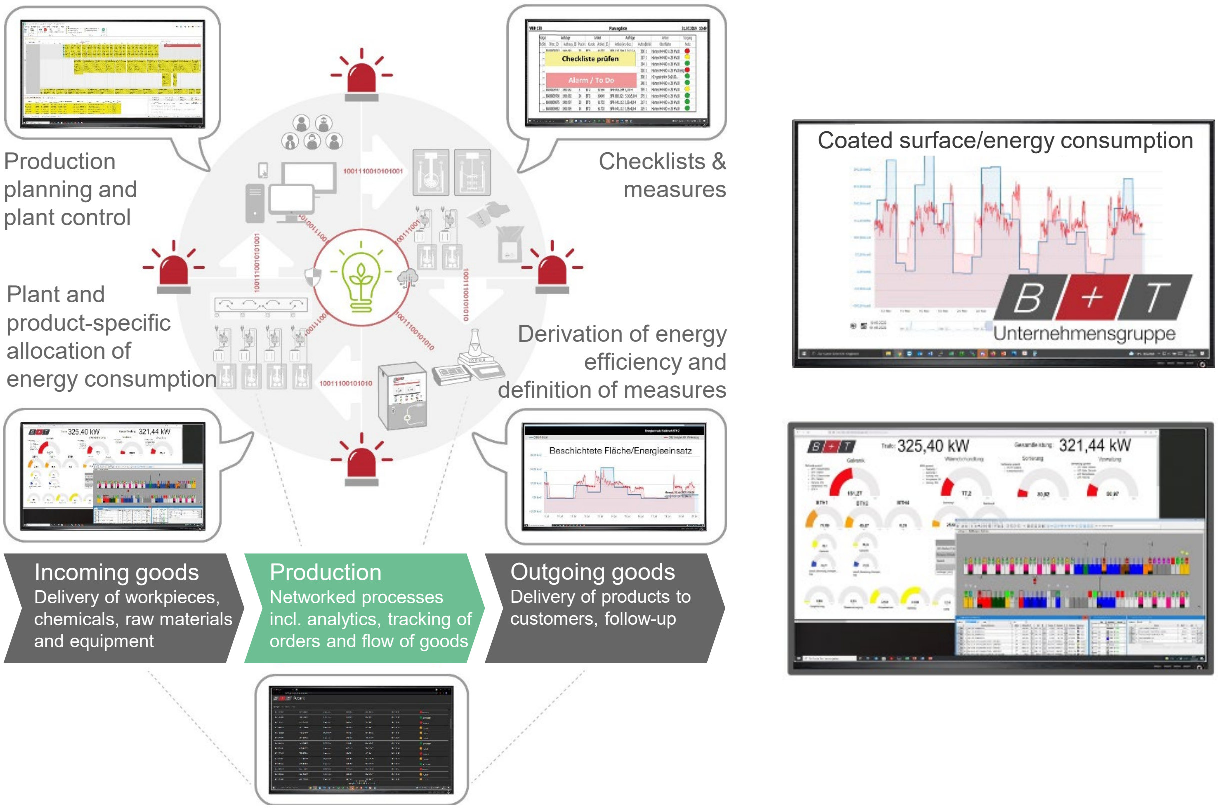


Figure 8: Process-specific data basis enables overarching transparency and opens up scope for action

BMW AG is also implementing numerous measures to create transparency and reduce energy consumption. In the first step, standardized energy modules were defined and transparency created by standardizing energy measurement technology and using a cross-departmental energy server, which enables **live energy consumption monitoring** within the plants concerned. The measures to increase energy efficiency were initiated at the Steyr plant and have since been rolled out at various other BMW AG plants, so that the energy server, for example, is used at various BMW AG plants worldwide. Energy indicators were derived from the energy data, such as base load power, energy consumption per product produced and the energy utilization rate within the value chain. Based on this, **improvement measures** were defined. Base load, for example, was reduced by shutting down equipment during non-production periods, reducing circulation times from three to four times per hour to once per day, and programming resource-saving modes for machine standby. In addition, pre-cooling and plant exhaust were shut down during non-production periods. These base load reduction measures alone saved 4.2 GWh per year at the Steyr plant, equivalent to the annual consumption of around 840 single-family homes.

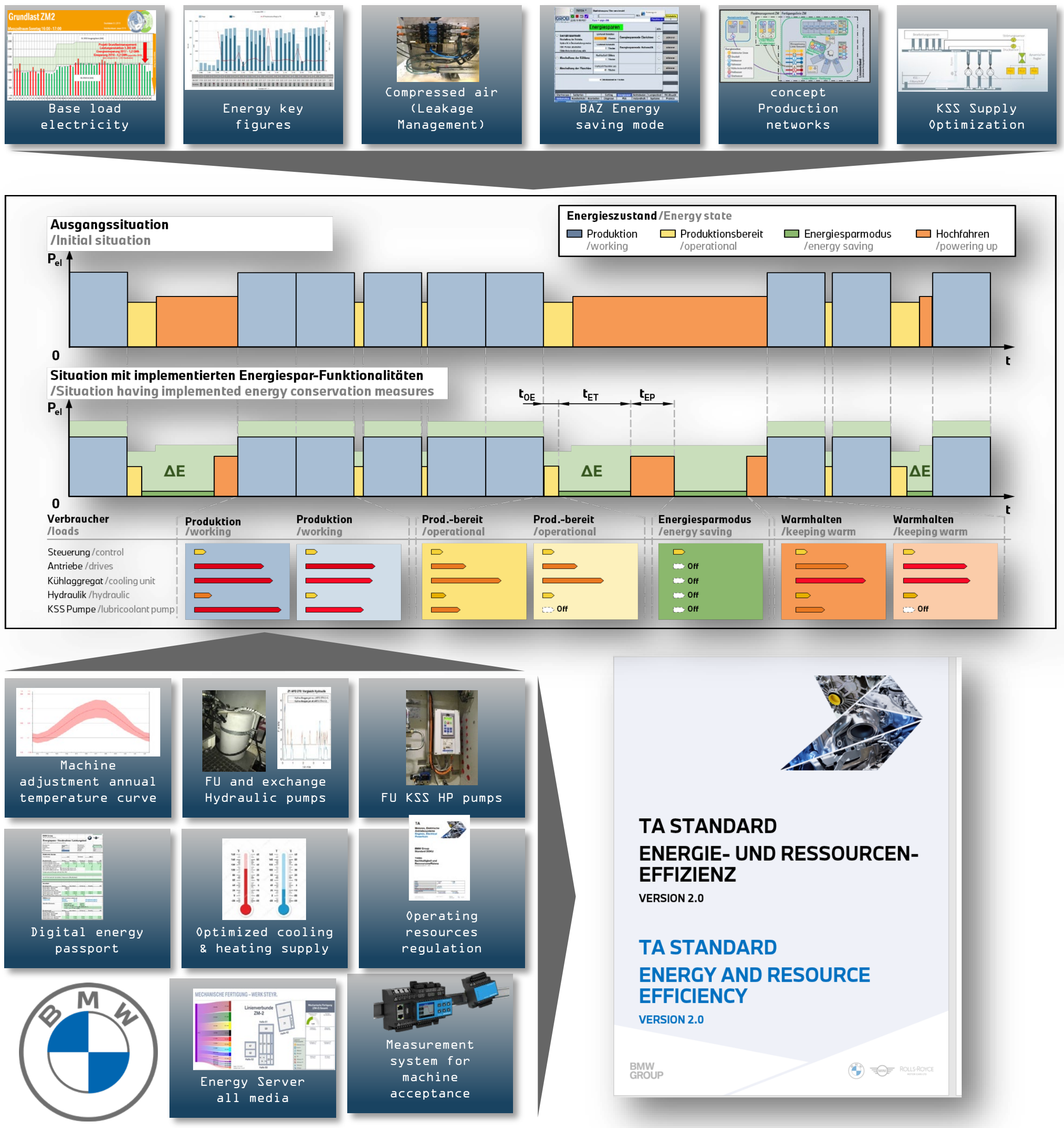


Figure 9: Creation of increased energy efficiency and standards based on standardized energy modules at BMW AG (excerpt).

The introduction of an energy-saving mode for machining centers resulted in savings of a further 2 GWh per year. The aim was to eliminate, as far as possible, energy consumption in non-value-adding non-productive times, as illustrated in the top of Figure 9. At the same time, energy efficiency in the value-adding processes was increased. The increase in efficiency in production also extended to the peripheral equipment. Equipping the high-pressure cooling lubricant pumps with frequency converters resulted in savings of 1.7 GWh per year. These control the pump speed using two controlled variables (pressure & flow rate). The savings of 27.1% were previously calculated by the Vienna University of Technology using simulation. Overall, the implementation of numerous individual projects (in addition to the projects mentioned, for example heating, ventilation and compressed air supply were also considered) saved 30% of the energy consumption of the production line under consideration. As a result of the energy efficiency projects implemented since

2016, recurring **annual energy savings of 28.7 GWh have been** achieved in production. Based on these findings, BMW AG continued to develop the Digital Energy Passport, an energy and resource efficiency standard that defines the energy efficiency requirements for plants to be procured in the future and thus becomes a future award criterion. The procedure for the creation of the energy module, the transparent visualization of the production data up to the implementation of improvement measures at BMW AG and the energy and resource efficiency standard that will apply in the future is summarized in Figure 9.

The practical examples show that significant energy savings can be achieved even with individual measures that can be implemented in the short term if, as a first step, transparency is created about the consumption in production and potentials can be identified on this basis.

4.2 Increasing the efficiency of machines

In line with the increasing requirements, as described above for example at BMW AG, machine manufacturers are striving to make their contribution to a more sustainable manufacturing in the future. In order to survive in a market with such requirements, machine and plant manufacturers as well as manufacturers of machine components are searching for effective levers for efficiency improvements in their products.

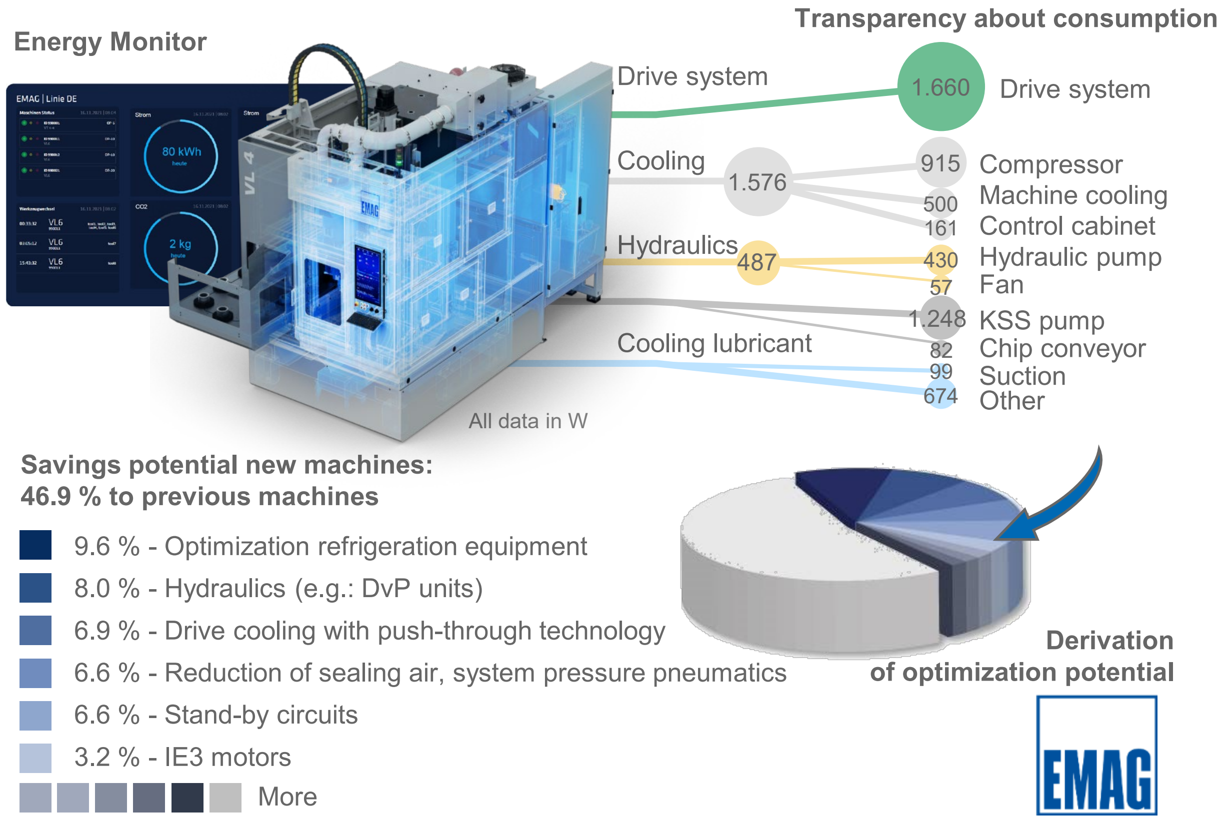


Figure 10: Breakdown of the energy consumption of a lathe [6]

In the past, EMAG GmbH & Co. KG already pursued measures to increase the efficiency of individual components, such as pumps or motors. A major lever for further efficiency improvement is the process-specific selection of optimally dimensioned machines. With its dashboard, the so-called EMAG Energy Monitor (see Figure 10), the consumption data of the machine tools are seamlessly integrated into an IoT platform and can be visualized and analyzed centrally, e.g. for an entire production line or directly on the machine.

An exemplary analysis result of energy consumption data of a lathe is shown in Figure 10 with a breakdown of the total power consumption into the individual components. It can be seen that the drives, the cooling of the components as well as the cooling lubricant supply and preparation cause the largest power consumption within the lathe. The availability of this data offers the **possibility of diagnosis and evaluation of efficiency-increasing measures**. Based on this, it was deduced in the EMAG example that the greatest potential for energy savings lies in optimizing the cooling units, hydraulics and drive cooling. Potential levers are, for example, the reduction of sealing air, stand-by circuits, IE3 motors or frequency-controlled auxiliary drives.

The spindle manufacturer GMN Paul Müller Industrie GmbH & Co. KG offers one approach to optimizing the drive system. If, for example, an electric motor is operated in a partial load range, this results in lower **efficiency**. The reduction in efficiency is significant depending on the motor type and efficiency class [12]. Therefore, the oversizing of spindles in machine tools should be avoided. However, to meet this requirement, knowledge of the operating point(s), i.e. the power consumption of the spindle as a function of the rotational speed, is necessary. Often, the user is not aware of the operating point(s) at which a spindle is operated or what power requirements the spindle has to meet during operation. Therefore, GMN developed a concept for Industry 4.0-capable IoT-ready high-performance spindles (see. Figure 11), which with an integrated data interface enables, among other things, runtime-dependent power recording. In addition, the acquisition of further relevant measurement signals, e.g. for condition monitoring, is possible.

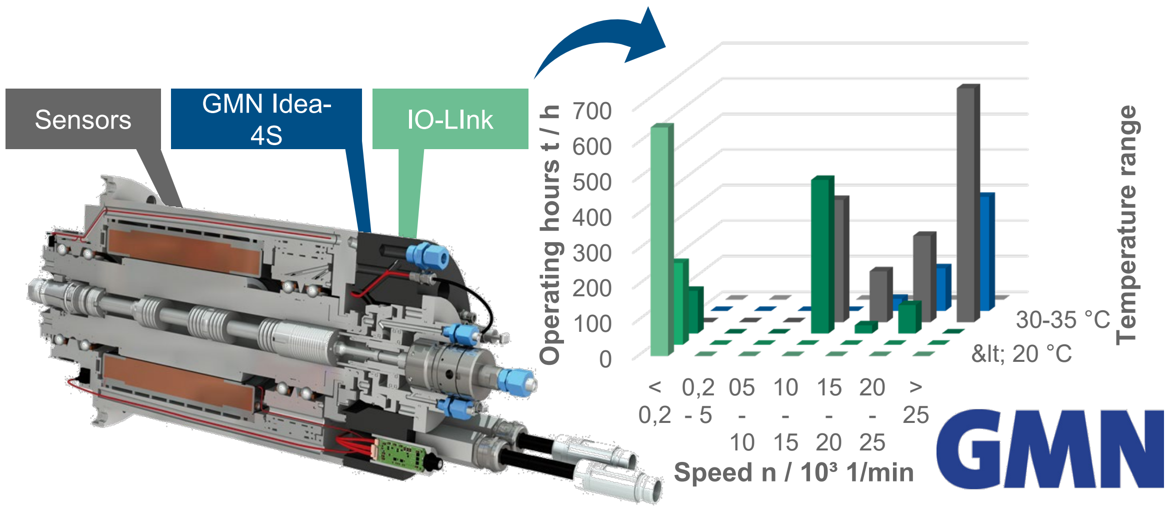


Figure 11: Increased demands on a spindle in machine tools [13]

This creates transparency about the real operating points and enables a customer-oriented, power-case-specific spindle design for the relevant operating points. Based on the knowledge of the real spindle requirements, a synchronous spindle with optimum maximum power can be developed, so that only the power actually required for the application (see Figure 11) is installed in the spindle and frequency inverter. Thus, on the one hand, *the overall efficiency of the spindle/machine can be increased and the use of resources for the acquisition can be reduced. [13]*

4.3 Increasing the efficiency of machine periphery using the example of cooling lubricant supply and preparation

A major lever for saving energy and increasing the efficiency of manufacturing processes is the cooling lubricant supply. For example, the **cooling lubricant supply in the grinding process** causes **more than 60 % of the energy consumption** [14]. Compared to other manufacturing processes, the cooling lubricant supply is of particular relevance in the grinding process because, due to negative rake angles and many parallel grain interventions, a high thermal load is generated, only a small part of which can be dissipated via the chips [15]. In addition, the disposal of cooling lubricant as hazardous waste burdens the environment and thus the ecobalance. There are several approaches to reducing the energy consumption caused by the supply of cooling lubricant and the quantity of cooling lubricant required.

One way of reducing both the required volume flow and the required pressure of the cooling lubricant and optimizing the cooling lubrication of the manufacturing process is to use process-specific and optimized nozzle concepts [15]. When optimizing the nozzle concept, the best possible combination of the mutually influencing parameters of resource conservation, process productivity and product quality must be found.

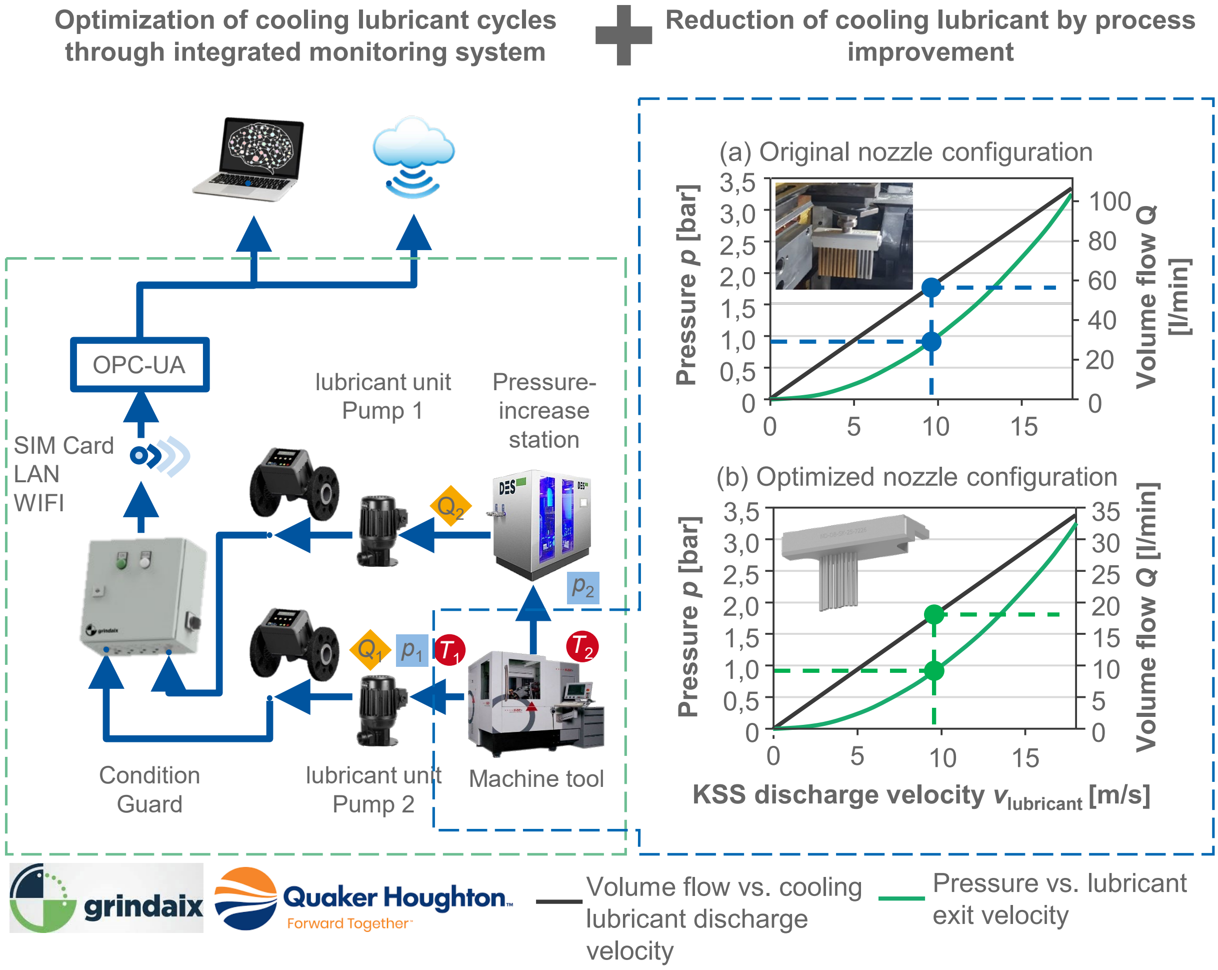


Figure 12: Optimization of the cooling lubricant supply by means of an adapted nozzle concept for external cylindrical grinding [16]

The potential for energy savings offered by the optimization of the nozzle concept is shown in the example of external cylindrical grinding from the company Grindaix in Figure 12 [16]. The original nozzle configuration (a) was too wide for the grinding wheel used. At a pressure $p_{lubricant}$ = 0.92 bar and an exit velocity of $v_{lubricant}$ = 9.6 m/s, this resulted in a volume flow $Q_{nozzle1}$ = 57 l/min. By using a needle nozzle (b) adapted to the grinding wheel geometry, the volume flow $Q_{nozzle2}$ = 18.11 l/min could be reduced by approx. 68 % at the same pressure $p_{lubricant}$ and the same exit velocity $v_{lubricant}$

Another way to optimize efficiency in the use of cooling lubricants in manufacturing processes is to systematically monitor the cooling lubricant supply. By monitoring the pressure, temperature and volume flow in all cooling lubricant circuits of a machine tool, it is known at all times how much cooling lubricant is flowing at what point. On the one hand, this makes it possible to minimize cooling lubricant-related downtime. In addition, the recorded data can be used to identify possible optimization potential in the cooling lubricant circuit.

An exemplary integration of a complete monitoring of the cooling lubricant circuit during tool grinding with a system of the company Grindaix is shown in Figure 12. In a project at the WZL | RWTH Aachen Uni-versity, all cooling lubricant circuits in a tool grinding process were monitored to identify optimization potentials [17]. By monitoring the cooling lubricant circuits, different cooling lubrication strategies were compared to improve the cooling lubricant supply in terms of productivity and efficiency. Overall, Grindaix achieved a 38% reduction in oil consumption, €85,000 annual savings in electricity costs for coolers and pumps, and €285,000 annual savings in cooling lubricant costs when implementing its own approaches to optimize cooling lubricant supply (demand minimization using nozzle technology and monitoring, demand-based control, and sustainable cooling lubricant solutions) in the production of a customer in the automotive supplier industry (customer demand for new oil: 185 tons per year). In addition, the continuous data recording and online data evaluation of the ongoing production can prevent possible machine failures due to the cooling lubricant supply.

Oil is used in a wide variety of applications in manufacturing technology. For example, hydraulic oils, gear oils, lubricating oils, compressor oils, rolling oils or machining oils are used. Oils have to be replaced after a certain period of use due to contamination, additive degradation and oxidation and so do cooling lubricants. To be able to use oils almost infinitely in the identical application, RecondOil, a startup belonging to the SKF Group, has developed a reconditioning technology. The circular use of oil not only results in a significant improvement in sustainability, but also leads to a reduction in process costs, as the procurement of new oils can be greatly reduced. In addition, manufacturing processes that do not use aged and contaminated oils due to continuous reconditioning are expected to experience an increase in performance.

Conventional filter systems filter particles larger than 1 µm. However, 80% of the contaminants in industrial oils consist of nanoparticles smaller than 1 µm. RecondOil adds a chemical booster to the contaminated oil that binds contaminant particles of all types and sizes (see Figure 13). This results in larger particles that separate from the oil due to their higher density and are either separated in a sedimentation phase or filtered out mechanically. On the one hand, the system can be used as a stand-alone solution in which the oil is removed from the actual process circuit. On the other hand, a solution integrated in the oil circuit is possible, which is mainly used in central cooling lubricant systems [18]. By using RecondOil, numerous improvements have been observed in pilot projects, both in terms of **environmental sustainability, economic efficiency and the quality of** the parts produced. The associated key figures are shown in Figure 13.

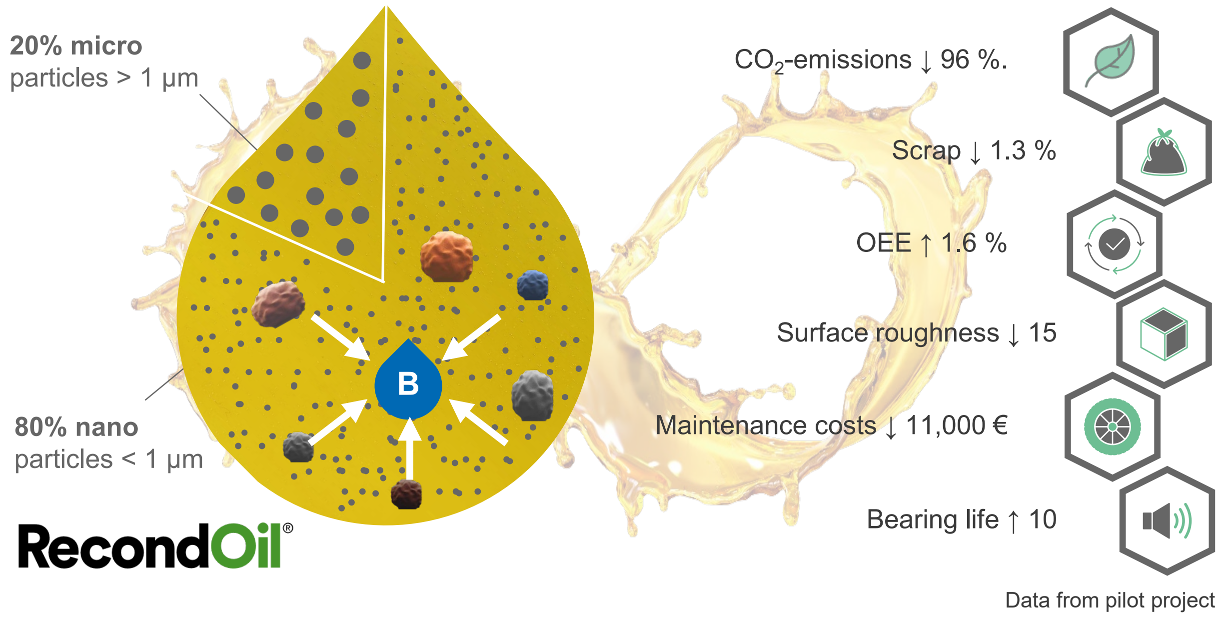


Figure 13: The RecondOil Booster binds nanoparticles in the oil [18]

5 Functional extension through process optimization in manufacturing

In addition to increasing the ecological and economical sustainability of manufacturing through innovative equipment cleaning IN manufacturing, products and their product life cycle can also be made more sustainable WITH manufacturing. 87.5 % of the CO_2 footprint of a machine is determined during the use phase. Therefore manufacturing must serve as an **enabler for improving the function of** a product in the medium and long term, so that increased efficiency and longer product life reduce the greenhouse gases emitted during the use phase and increase material efficiency, among other things.

Reduced friction in rolling contacts due to interface layer formation during production

Increasing the functionality and service life of rotating products can be achieved, among other things, on the production side by optimizing the product properties. In addition to reducing friction by adapting the surface geometry, interface layers, which are formed during grinding due to interactions between the workpiece surface and the cooling lubricant used, contribute to friction reduction and wear protection.

Furthermore, they influence the further layer formation during operation in rolling contact with the lubricant used there. Thus, a targeted selection of additives in the cooling lubricant and the grinding parameters reduces the friction during operation and thus the power loss. Experimental grinding tests at the WZL | RATH Aachen University have shown that by selecting suitable feed rates during grinding, which directly influence the thermomechanical loads in the contact zone, a parameter optimum was achieved with regard to minimum coefficient of friction μ and maximum service life. This was explained by the different elemental composition of the outer interface layer (F, O and Si occupation) (see Figure 14).

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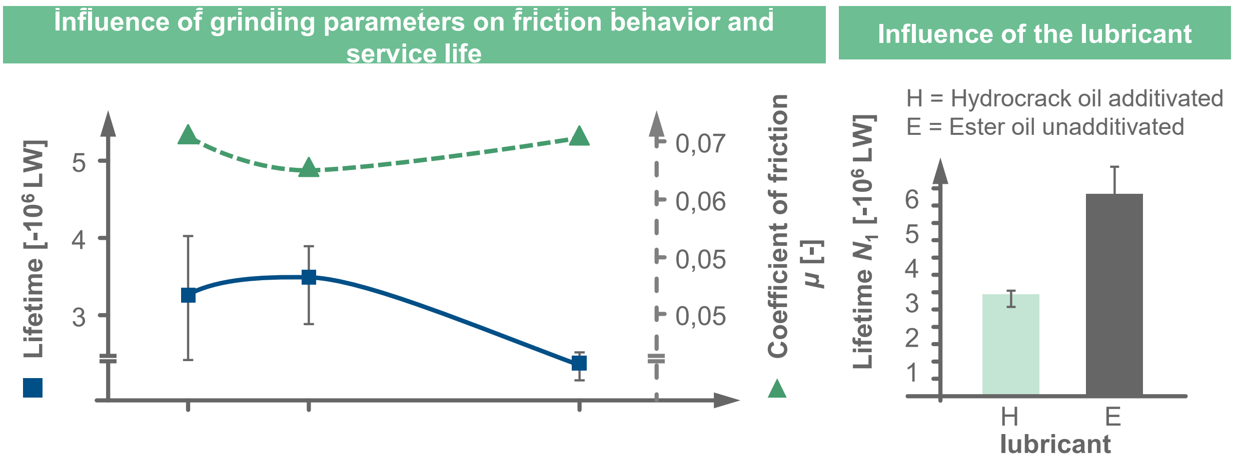
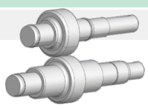


0,03	0,05	0,10	Feed rate for finishing v_{fr2} [mm/min]
0,25	0,30	0,32	Center-line roughness Ra [µm]
-388	-371	-350	Residual stresses surface [MPa]
74	70	68	Fe-occupancy [at-%]
6	11	14	O-occupancy [at-%]
0,7	1,0	1,0	Si-occupancy [at-%]



Object of observation: two-disc tribometer

Figure 14: Influence of grinding on friction and service life in rolling contact.

When an unadditivated ester oil was used, the lifetime was found to be twice that of the additivated hydrocracking oil. [19]

Increasing service life in the example of gearboxes and electric drives by manufacturing tribologically optimized functional surfaces

Gear drives such as those in electric cars or aircraft engines are used everywhere in mechanical engineering to transmit power and control speed and torque. In gears, a lower tooth flank roughness has a positive effect on the load-bearing capacity of a tooth flank. Low roughness is produced, for example, by generating grinding. An additional fine or polishing grinding process with ceramic or elastically bonded corundum following the conventional gear grinding process produces lower roughness and a higher material content. In load capacity studies (see Figure 15) it was shown that significantly higher flank pressure is possible with the fine and polish ground gears. The results show that a **higher service life** was achieved at a constant nominal flank pressure σ^*_{HO}. Despite an initially higher CO_2 footprint from the production of semi-finished products and manufacturing, the increase in service life due to the fine or polishing grinding process thus leads to **resource conservation** by ensuring extended functionality in the service life phase. For the maximum service life investigated, the maximum possible nominal flank pressure σ^*_{HO} was increased by a fine grinding process. This allows the design of more compact gearboxes with higher power density, which save resources in the use phase of the gearbox due to a lower weight and a lower moment of inertia. [20]

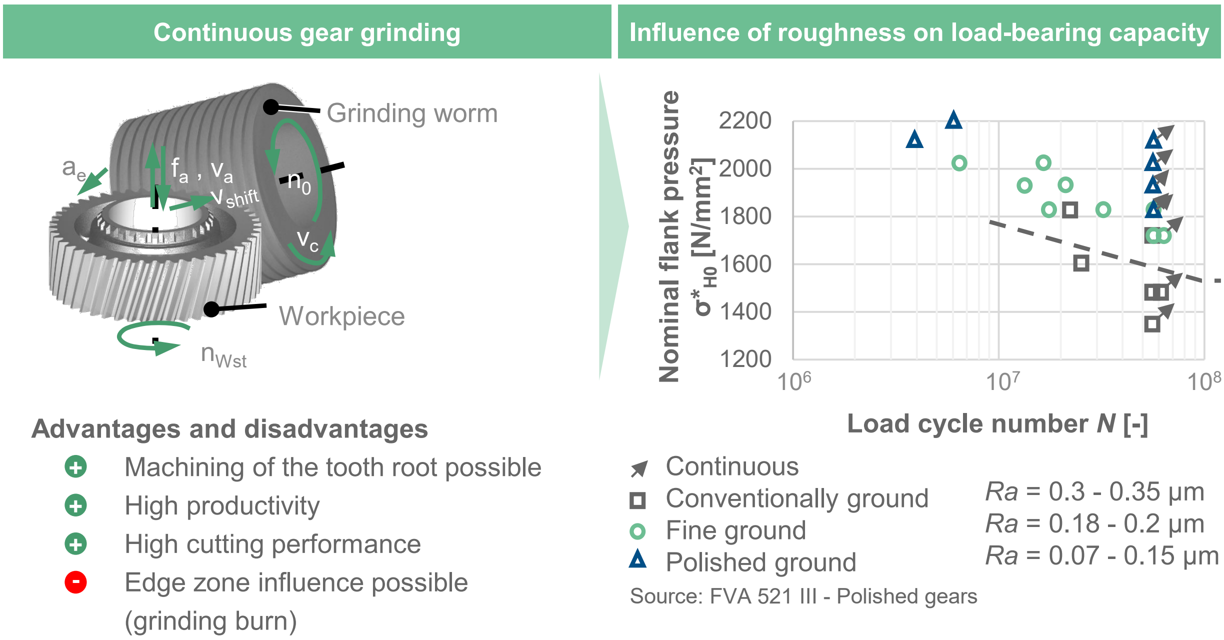


Figure 15: Influence of grinding on the load-carrying capacity of tooth flanks

Rotor shafts of electric motors are another example where tribologically optimized functional surfaces can contribute to resource conservation. Compared to internal combustion engines, electric drive trains operate at significantly higher speeds. However, the resulting higher temperatures and higher sliding speeds pose major challenges for the associated sealing technology. To ensure that the service life of resource-saving systems is not limited by inadequate sealing capability, not only the sealing elements but also the tribological properties of the sealing counterface must be optimized during production. Ground surfaces, especially in contrast to turned surfaces, consist of a large number of individual structures which, due to their double convergent shape, lead to the buildup of a wear-protective lubricating film during shaft rotation. Grinding is therefore the standard process for producing sealing counterface. However, under unfavorable conditions, the orientation of the individual grinding structures can deviate from the circumferential direction during plunge grinding.

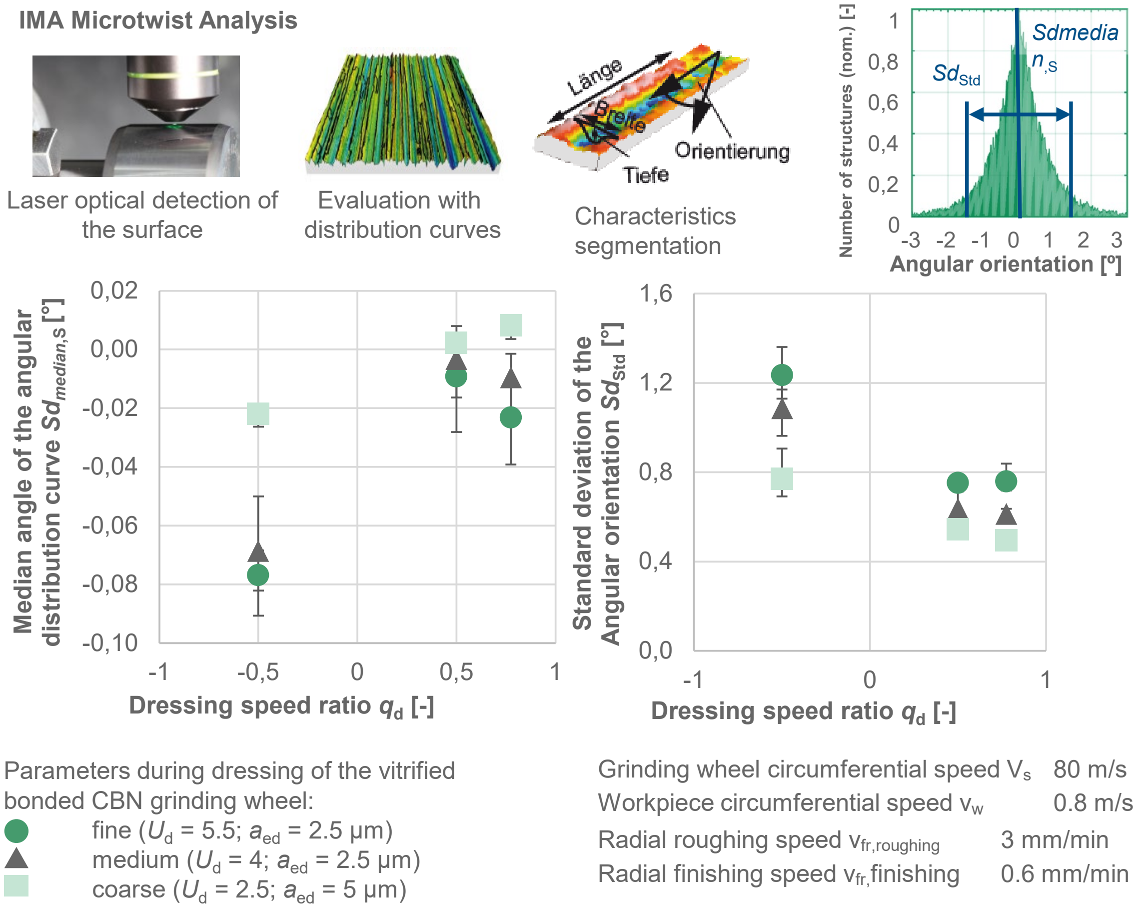


Figure 16: Influence of dressing parameters during grinding on the micro lead structures

This so-called micro lead is particularly damaging to a sealing system due to the high conveying effect at high speeds. Therefore, this must be avoided during grinding by using a knowledge-based process design. In the micro lead analysis of the Institute for Machine Elements IMA at the University of Stuttgart, optical measurement technology is used to detect every surface structure and determine its orientation and geometry. Suitable sealing counterfaces are present if the normalized number of structures plotted against the angular orientation exhibits a distribution curve that is as broad and symmetrical as possible, with a main maximum at an angle of 0°. The width of the distribution curve is described by the standard deviation of the angular orientation Sd_{Std} , the position of the main maximum by the median angle of the angular distribution curve $Sd_{median,S}$. Experimental investigations have shown that with negative dressing speed ratio q_d , i. e. when the velocity vectors of the forming roll and the grinding wheel point in different directions and thus there are shallow pressure angles between the dressing diamond and the abrasive grain, the median angle of the angle distribution curve $Sdmedian_{,S}$ deviates significantly from the circumferential direction (0°). [5] Due to the tribological properties of ground surfaces, the manufacturing process thus offers great potential for improving the friction and wear behavior of drive components in such a way that, overall, a **significant contribution** can be made to **resource conservation in the context of the mobility revolution.**

6 Material efficiency and circular economy

As already stated, the goal must be to minimize the emissions attributable to a product over its entire life cycle. The design phase and end of life must also be taken into account. In addition to energy, material is also consumed in manufacturing. Any material that is disposed of as offcuts and waste has also caused environmental impacts in its production and processing up to this point. In a complete balance, these must be shared by the products sold. Therefore, it is important to design the use of materials as efficiently as possible and to minimize waste, also from an economic point of view.

Furthermore, the engineering phase is a lever for **improving the recyclability** of the product. If the recyclability is already taken into account in the material selection and product design, components can be more easily fed into different R-scenarios by using monomaterials or modular design.

6.1 Material efficiency through process innovation

Individual product components and their production also play a major role in increasing the material efficiency of products. The Schaeffler Group, a leading global automotive and industrial supplier, who is driving forward inventions and developments in the areas of motion and mobility, such as the production of hydrodynamic plain bearings for high-performance wind turbine gearboxes from the industrial division, shows how the production of gearbox components in wind turbines can make a decisive contribution to ecological sustainability in the future through **alternative process chains and an associated increase in material efficiency** both in production and in the use phase and enable an increasing circular economy of the manufactured technical products. Since the wind turbine will play a key role in the future production of green hydrogen, which is needed for an energy turnaround, the effect of such measures is particularly great.

One of the components of the wind turbine's gearbox shown in Figure 17 is the plain bearing from Schaeffler. The current state of the art is bronze bushings pressed onto the planetary gear pin. The **conventional process chain** consists of a total of 21 individual process steps, the most important ones are explained below. In the first step, the steel bolt is machined and fine-tuned. This is followed by the assembly of the functional bronze bushing with a wall thickness of 15 mm.

The bronze bushing is produced by melting the alloy in a centrifugal casting process and then **contoured in a subsequent turning process**. This is followed by stress-relief annealing, followed by a precision turning process and joining of the bushing to the steel bolt pin by an interference fit. The resulting material consumption of the bronze bushing is 30.6 kg of the alloy used, which corresponds to a CO_2 equivalent of 156.7 kg per part. The consistent further development of this plain bearing is the direct coating of the bolt with the aid of modern additive manufacturing. The **innovative and greatly shortened process chain** shown in Figure 17 by incorporating a laser cladding process has a high geometric flexibility. In addition, this process guarantees a strong material bond between the steel bolt and the bronze functional layer. The entire process chain can thus be reduced to just 14 process steps, the most important of which are the machining of the steel bolt, the direct laser cladding on the steel bolt and the final finishing (see Figure 17).

At the same time, the process-related reduction of the functional layer thickness to 1 mm instead of 15 mm allows a reduction of the bronze material to only 2.9 kg, which resulta in a material reduction of up to 90%. The associated CO_2 emissions are thus reduced to 14.7 kg.

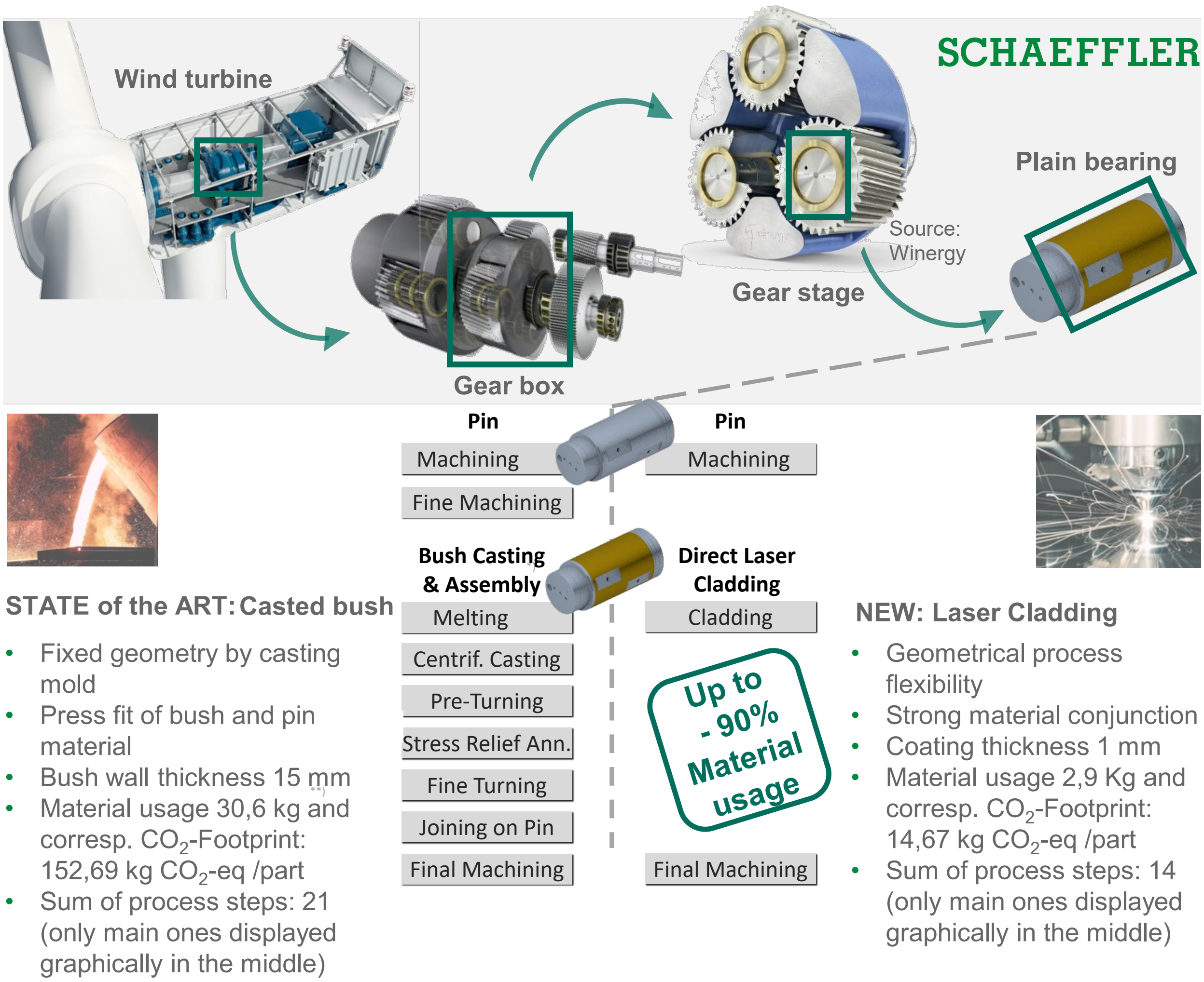


Figure 17: Material efficiency through process innovation and innovative process chain for transmission components at the Schaeffler Group

The example impressively demonstrates the extent to which a technology/process innovation and innovative process chains can contribute to increasing production and material efficiency and the role they can play in effectively shaping sustainable value creation in a future circular economy.

An exemplary scenario opens up in the reuse in other product groups of the Schaeffler Group via a repair cycle, in which a component machined with this process, after turning off the worn bronze functional layer, is guided directly into the utilization cycle and reused with a reapplied functional layer. Thus, material efficiency can be further maximized over the cumulative life cycles of the components.

6.2 Material efficiency through material optimization for recycling and circular economy

In order to increase the contribution to sustainability made by manufacturing, the recycling of materials represents great potential in addition to measures to extend service life, i.e. maximizing functionalization life. Material recycling returns materials to the material cycle and saves primary resources, energy and emissions through the use of secondary materials compared with initial material production. At the same time, waste that would otherwise be thermally recycled is avoided. Thus, by recycling materials and substituting virgin material with recycled material in manufacturing, a significant contribution can be made to sustainable production. [21] In the context of recycling materials, it should be noted that good material separation is required, especially for the reuse of materials, in order to achieve unmixed materials. However, material separation is currently often still a major challenge. This is due to the fact that today's products often consist of different materials and complex compounds which, due to their design, are difficult to separate or can only be separated with great effort. Furthermore, contamination poses a challenge and makes material separation more difficult. Especially when automated separation is not possible and manual sorting processes are required, material separation can be very costly. [22], [23]

One way to meet these challenges is to increase the use of monomaterials in manufacturing. Monomaterials consist of a single material. In contrast, many conservatively manufactured products are made of different materials that are glued, welded or otherwise bonded together. Monomaterial products can also reduce the risk of material separation failures, which increases the efficiency of recycling processes. Therefore, monomaterial products are seen as an important component of a sustainable and circular economy and will be used in the future in various industries such as packaging, consumer goods, and construction. [23] At best, the manufacturing industry will also experience continuous change in terms of the material groups that can be used and are available.

A promising approach to the use of monomaterials is being pursued by the company Carcoustics. By using monomaterials as absorber material in the interior of cars, the recyclability of the components used can be increased (see Figure 18). These components can be completely **recycled** (III) by melting them down and reusing them as high-quality secondary material. This means that no complex mechanical material separation is required for recycling. Due to the melting down of the monomaterials and the production of recycling material with virgin material quality, no separate process control is required, as the material can simply be reintroduced into the production process. In addition, Carcoustics is increasingly using recycled material instead of virgin material. One application are acoustic absorbers. For this purpose, scrap parts or process-related offcuts are shredded and then used as **recycled production waste** for absorber products. Production waste recycling attempts to reduce the amount of rejects and material waste generated during production and to recycle any residual materials. In the example of Carcoustics this not only increased product sustainability through recycling, but additionally improved the acoustic properties of the absorbers. It is therefore evident that recycling not only brings ecological and economic benefits, but can also be accompanied by an increase in component functionality. In this type of material recycling, however, it should be noted that the material properties cannot be directly compared with virgin material, which is why other, factors, that did not play a role when using virgin material must be taken into account in the process control. To ensure component quality in this example, it must be ensured, that the shredded flakes are evenly distributed during processing.

The examples provided by Carcoustics show that recycled material can be used in numerous applications without compromising the quality of the end product. The potential of recycling is currently not fully exploited, however, primarily because there is a lack of suitable and standardized solutions for collecting the components or materials after use and returning them to the industrial cycle. The aim of product recycling (II) is to reuse the product in the same or in another area of application, for example with lower requirements, which mens that the same functional performance must be given. In **product recycling,** a distinction is made between recycling at element level (reuse of individual components or assemblies) and system level (reuse of the entire product). In order to meet this challenge, the igus company offers its customers the return of manufactured and used energy chains after the use phase as part of the igus Chainge program. The material is sorted by type, cleaned and processed to new product quality. The material is then returned to the material cycle. Thus, almost 100% of the primary material is reused in **element product recycling.** In this case, not only energy chains with the same material quality are achieved, but also CO_2 emissions are reduced by 28% through a sustainable raw material cycle. [22], [24]

At the end of the product's service life, the original materials of the product are recycled (III). Here, the materials can either be fed directly back into material production or, after thermal or chemical processing, back into raw material production. In addition to saving energy compared to the production of new raw materials, recycling offers potential for reducing dependence on raw material supply. The company Ceratizit uses this potential in the **raw material recycling** of hard metal. By using more than 99% of high-quality secondary raw materials (for example worn carbide cutters) collected from customers by a specially designed service, it is possible to reduce raw material dependencies on critical primary raw materials (such as cobalt). In addition, CO_2 emissions are significantly reduced through the use of innovative low-emission production processes, sustainable energy sources and short transport routes. The example (see Figure 18) shows that the quality of products produced using secondary raw materials, made possible by the use of innovative process optimization or the substitution of process routes, does not have to be lower than when primary raw materials are used.

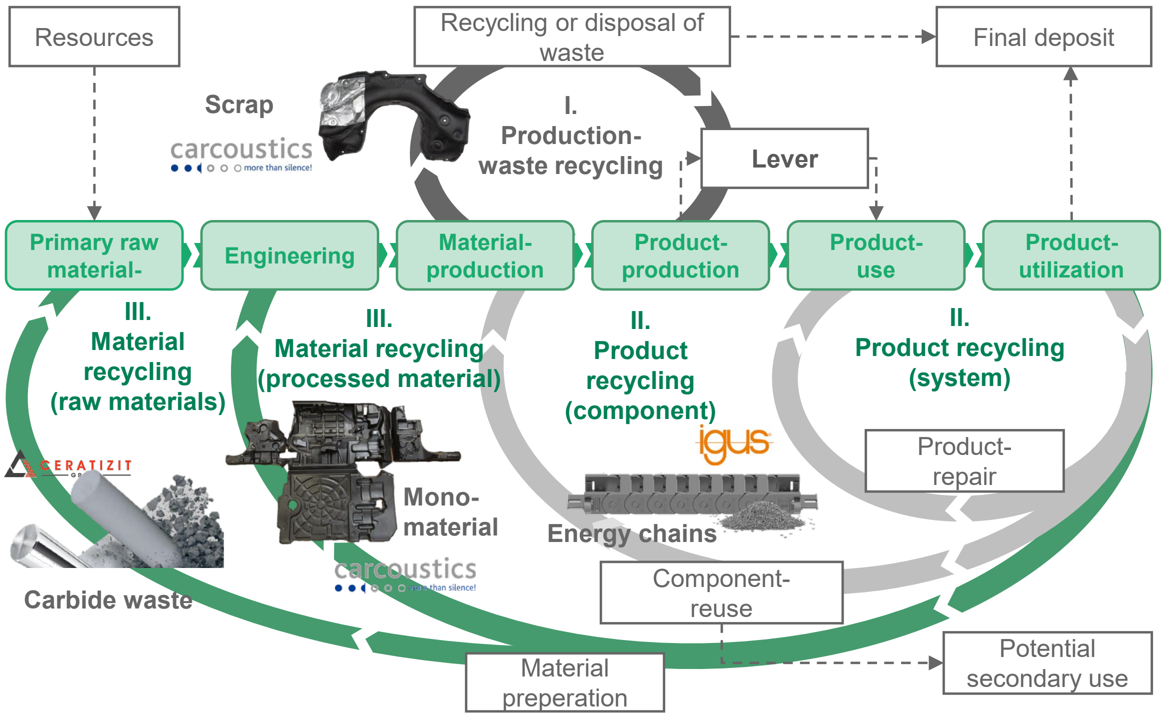


Figure 18: Classification of recycling in the materials cycle

7 Product-specific optimization of product life cycles with the help of manufacturing and the digital twin

As outlined in the previous sections, various approaches exist for increasing energy and material efficiency in manufacturing and in product use and recycling, as well as the associated CO_2 emissions. It was also shown that a multi life cycle approach is required to holistically assess the emissions directly associated with a product. This requires not only the recording of local emissions in manufacturing, but also at other points such as logistics, use and recycling. In addition, a one-sided view of emissions neglects the effect of potential levers in manufacturing that have a positive or negative impact on emissions in other lifecycle phases; instead, the goal must be to minimize a product's overall evironmental footprint. Consequently, in the case of the marine engine, it is ecologically beneficial and also profitable from an economic point of view to accept increased CO_2 emissions in the production of the marine engine, e.g. through optimized machining processes or through the adaptation and further development of technologies, as long as this leads to a correspondingly large reduction in emissions over the product use phase. Here, retrofit-friendly product design and a consciously accepted increase in retrofit accuracy also play a special role (see Figure 19), as this can extend the overall service life of the product. Functional surfaces in the engine influence its efficiency. If functional surfaces are specifically optimized by adapted manufacturing technologies, these measures have an effect on product operation. Due to the significantly greater **leverage of product operation,** improvements to the overall system can thus be implemented particularly WITH manufacturing. By optimizing the function of the product in the use phase, for example a reduction in CO_2 emissions or an improved circular economy balance can be achieved through service life extensions. In the case of the acoustic absorber from Carcoustics, the influence of the product use phase on the overall resource consumption and emissions is significantly lower than the influence of the production phase. The absorber has no influence on the service life of the car and affects its emissions only through its own weight, which is, however, very low and therefore offers comparatively little leverage for optimizing emissions in the use phase. Although the ecological impact cannot be dismissed due to the number of cars that exist and the acoustic absorbers installed in them, the predominant lever for ecological **optimization with this component** lies in **the production phase and the reusability** of the materials used.

The examples illustrate the need to consider complete product life cycles when evaluating the emissions associated with the product. The life cycle of a product begins with its conception and development, followed by raw material production, manufacturing, distribution and transport. This is followed by the functional fulfillment in the product's use phase, which can be additionally extended by repair measures or further recycling approaches. This provides further considerable leverage for reducing the CO_2 balance of the product. Identifying the **product-specific optimal R-scenarios** requires a life cycle assessment on a suitable data basis, comprehensive knowledge of the functional/product/component properties and the use phase (service life, load cases, etc.). Here, the application of digital twins offers high potential, as they map a virtual representation of a real physical object, process or system as a digital model (for further information, see the article **Manufacturing for a Circular Economy**). This twin is based on manufacturing and usage data and processing algorithms as well as physical product properties, so that in addition to replicating the real object, simulations for further life phases or usage scenarios are possible. At the same time, this allows potential problems or weak points to be identified in advance and measures to be taken to correct them before they lead to costly failures or malfunctions. In this context, wide-ranging **predictive quality** approaches offer the potential to maximize product life while detecting failures early and avoiding critical component failure. The digital twin can also be used to identify valuable **data for optimizing recycling loops** and the interactions between loops. The digital twin thus provides the link between the pre-predicted life cycle and the ongoing assessment and optimization of future use scenarios.

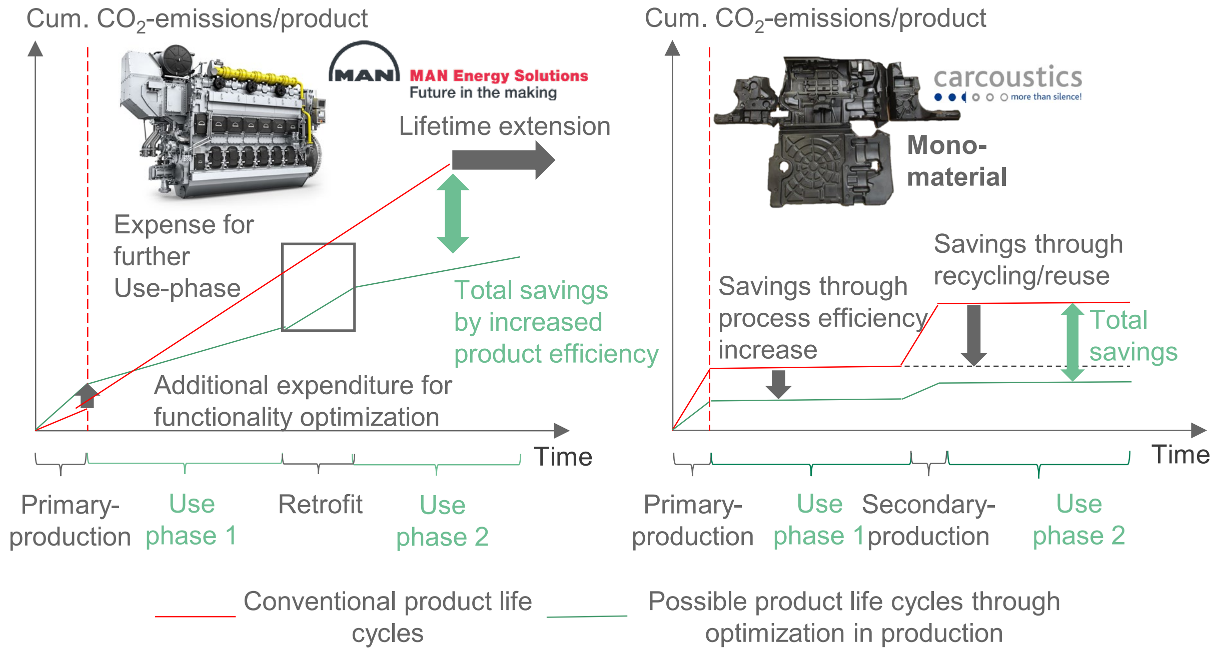


Figure 19: Schematically depicted product-specific leverage effects from manufacturing to emissions in the use phase.

For **sustainability assessment of the overall life cycle,** the **digital twin** can make predictions about life cycle emissions. In the overall consideration of the life cycle for the identification of optimization potentials, the digital twin thus represents an important tool in the future for linking the production and use phase(s) for CO_2 -optimized product design, production, use and subsequent implementation of R scenarios.

8 Summary and outlook

In order to improve ecological sustainability, manufacturing companies are currently focusing above all on energy and material efficiency in their own production. Companies that have already taken the initiative in this area are already leveraging a great deal of potential for energy savings and recycling valuable materials for the first time. However, broad, successful implementation requires the commitment of all those involved along the respective value chains, as well as exchange among those involved. This article therefore presents current best practices for increasing energy and material efficiency in manufacturing, which are already being implemented at and with OEMs, component and machine manufacturers, equipment suppliers and manufacturers of sensor and monitoring systems. As an enabler, manufacturing will play a key role in the production of more sustainable products in the future. A significant contribution to a sustainable circular economy can be made both in manufacturing itself and with the increase in product efficiency, functionality and energy and material efficiencies theat can be achieved WITH manufacturing. The examples presented show how both individual measures and measures based on data-based transparency can together pave the way to more sustainable production. Increasing the efficiency of machines and their peripherals, process innovations, but also product design and the materials used each play an important role. The methodological basis for evaluating suitable measures is provided by the ecological assessment. The data required for this can often already be collected and used within production today. However, with regard to the realization of product-specific sensible R-scenarios for the realization of a sustainable circular economy, there is an increasing need for product information also from the further life phases of a product. In the future, the concept of the digital twin will offer a promising approach for combining and processing all relevant process and product data so that a circular economy can be realized in production for a sustainable society in the medium to long term.

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2.3 Scalable Production of Energy Storage Systems

C. Brecher, H. Janssen, D. Zontar, M. Kersting, S. Rieck, K. Bär, T. Bastuck, S. Witt

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Abstract

Scalable Production of Energy Storage Systems

The production of energy storage devices, especially batteries and fuel cells, is a growing market in Europe, which opens new market opportunities for machine suppliers. The production of LIB cells consists of electrode manufacturing, cell assembly and cell finishing. Production of future cell formats and cell chemistries is difficult due to little synergy with current LIB production and requires research to optimize and streamline processes. Regardless of the development of processes for tomorrow, there is a high need for innovation of conventional production processes. One possible solution is data-driven production optimization. In the area of PEMFC and PEMEL, production is not yet high-volume capable, but there is a high demand for technologies to scale up. A current barrier to faster scaling is the transfer of catalytic layers from decal support films to the membrane. Viable solutions are seen in direct coating processes and flexible machine concepts. Overall, it can be concluded that there are many research approaches to improve existing production equipment and thus generate global added value. A transfer to the manufacturing industry is necessary to build next generation production lines that ensure a competitive advantage. To maximize the quality of the product and reliability of the assets, it is imperative to draw on knowledge and models derived from data acquired at existing machinery and research equipment. During the market ramp-up, European industry can take part in the value creation in the field of energy storage production in the short term by using existing, bought plant technology. In the long term, further development or the construction of in-house developed production machines is necessary to be able to produce the next generations of energy storage components and systems competitively.

Keywords: Energy storage, batteries, fuel cells, electrolyzer

Kurzfassung

Skalierbare Produktion von Energiespeichern

Die Produktion von Energiespeichern, insbesondere von Batterien und Brennstoffzellen, ist ein wachsender Markt in Europa, der für Maschinenlieferanten neue Marktchancen eröffnet. Die Produktion von LIB-Zellen besteht aus der Elektrodenherstellung, Zellmontage und dem Zellfinishing. Die Produktion zukünftiger Zellformate und Zellchemien ist aufgrund von wenig Synergien zur aktuellen LIB-Produktion schwierig und erfordert weiterhin Forschungsarbeiten, um Prozesse zu optimieren und zu verschlanken. Unabhängig von der Entwicklung der Prozesse für morgen besteht ein hoher Innovationsbedarf konventioneller Produktionsprozesse. Ein möglicher Lösungsansatz ist die datengetriebene Produktionsoptimierung. Im Bereich der PEMFC und PEMEL ist die Produktion noch nicht hochvolumenfähig, jedoch besteht eine hohe Nachfrage nach Technologien zur Skalierung. Ein aktuelles Hemmnis zur schnelleren Skalierung besteht im Übertrag der katalytischen Schichten von Decal-Trägerfolien auf die Membran. Lösungsansätze werden in direkten Beschichtungsverfahren und flexiblen Maschinenkonzepten gesehen. Insgesamt lässt sich feststellen, dass es zahlreiche Forschungsansätze gibt, um die vorhandenen Produktionsanlagen zu verbessern und damit einen globalen Mehrwert zu erzeugen. Insbesondere ist eine Überführung in die produzierende Industrie notwendig, um Produktionslinien der nächsten Generation aufbauen zu können, die einen Wettbewerbsvorteil sicherstellen. Zur Maximierung der Produktqualität und Zuverlässigkeit der Anlagen, ist es notwendig bei der Entwicklung auf Wissen und Modelle, basierend auf an bestehenden Anlagen und Forschungsausrüstungen akquirierten Daten zurückzugreifen.

Die europäische Industrie kann während des Markthochlaufs kurzfristig an der Wertschöpfung im Bereich der Energiespeicherproduktion partizipieren, indem bestehende, zugekaufte Anlagentechnik verwendet wird. Langfristig ist eine Weiterentwicklung oder der Aufbau eigenentwickelter Produktionsmaschinen notwendig, um die nächsten Generationen von Energiespeicherkomponenten und Systemen wettbewerbsfähig produzieren zu können.

Schlagwörter: Energiespeicher, Batterien, Brennstoffzellen, Elektrolyseure, Datenwertschöpfungskette

1 Introduction

The demand for renewable energy is driven by several factors. One major driver is the increased awareness of global warming. International regulations have come into force to reduce greenhouse gas emissions, which are known to have a significant impact on climate change. As part of its ambitious goals to reduce greenhouse gas emissions, the European Union (EU) has agreed to reduce greenhouse gas (GHG) emissions by 2030, by up to 40%. Since the use of fossil fuels causes GHG emissions, government regulations and policies directly affect fossil fuel consumers, such as internal combustion engine (ICE) vehicles and power plants that run on fossil fuels [1].

Reducing the number of internal combustion engine vehicles is considered a lever for reducing GHG emissions. In addition to the environmental damage caused by GHG emissions, health damage is also caused by the emission of pollutants such as nitrogen oxides (NO_x). As urban regions in particular suffer from air and noise pollution from ICE vehicles, more and more cities are introducing driving bans for certain ICE vehicles. A ban on new registrations of ICEs has been set for 2035 [2]. Moreover, governments around the world are not only regulating internal combustion engine driving through taxes and bans, but also promoting vehicle electrification at the same time. The trend in the mobility sector towards electric powertrains is reflected in the steadily growing number of electric (BEV), plug-in hybrid, and fuel cell electric vehicles (FCEV). In 2021, the number of electric cars worldwide passed the 17 million mark, a 1.7-fold increase [3]. This demand for electric vehicles is driving interest and investment in the development and manufacture of mobile energy storage technologies. In addition to battery storage, these include hydrogen fuel cells, particularly for commercial vehicles. By 2030, more than 1 million FCEVs will be produced [4].

For a successful switch to renewable energies, it is crucial to close the cost gap between electric and conventional solutions for stationary and mobile energy storage and energy converters and to meet the specific technical requirements of the various applications. Decisive levers for cost reduction in production are scaling up to high volumes and increasing the efficiency of individual manufacturing processes.

The increasing demand for energy storage systems represents a major opportunity and at the same time a challenge for mechanical and plant engineering and the manufacturing industry. These include strong market growth during the market ramp-up phase and, at the same time, short development cycles for the next product generations, which require new types of manufacturing processes. In order for companies to make an informed decision on new strategic directions and investments, a detailed examination of the various technological options for mobile energy storage is essential. Equally important is the development of novel production processes to be competitive in the future.

1.1 Energy storage and its application

Of the various technological options for climate-neutral mobile energy storage technologies, batteries currently have the largest market share. In particular, lithium-ion batteries (LIBs) are used in applications such as battery electric vehicles (BEVs). However, other storage and conversion technologies such as solid-state batteries (SSBs), or fuel cells (FCs) will also have to be increasingly considered in the future.

The various technologies have specific property profiles and differ in their technological maturity, their market potential for different applications and the production processes required. The main technologies are therefore briefly explained below:

Lithium-ion batteries (LIBs) are electrochemical energy storage devices capable of converting chemical energy into electrical energy. Depending on the use and specific design of a LIB, its lifetime can reach several thousand charge and discharge cycles.

Single LIB cells come in three different formats: cylindrical cells, prismatic cells and pouch cells. A LIB has two electrodes: the cathode, defined by the reduction during the discharge phase, and the anode. LIBs differ depending on the materials used for the anode and cathode [5]. The cathode is lithium-based and the anode typically consists of carbon materials such as graphite. Between the electrodes, there is a liquid ion-conducting electrolyte and a separating layer to insulate the electrodes. Both electrodes are coated on a current collector.

Figure 1: Exemplary illustration of a prismatic cell of the Fraunhofer FFB (Source: Fraunhofer FFB)

To achieve the required electrical power, several cells are connected in series (increasing the voltage) or in parallel (increasing the maximum discharge current). Interconnected cells are combined to form a module, and several modules form a battery system, also called a battery pack. The complete battery system includes these battery modules as well as electrical and mechanical components such as enclosures, insulation, cooling, fasteners, and the battery management system (BMS) [6].

In terms of energy density, LIBs cover a range from 230 to 300 Wh/kg. Values of up to 360 Wh/kg are expected for the future [7]. LIBs are used as power supplies for portable electronic devices and BEVs, as well as in stationary applications. It is expected that the global demand for these products will continue to increase [8]. At what point in the future LIB technology will be replaced by SSB is still a matter of discussion. Therefore, LIB technology will be evaluated as an example for the production technology challenges in the further. However, a possible transfer of synergies in production towards SSB must already be taken into account.

A **fuel cell (FC)** converts chemical energy of a fuel, in this case hydrogen, into electrical energy. In general, FCs consist of two end plates and a series of interconnected cells. The design of the stack and its components depends on the type of FC.

Depending on the operating temperature, FCs are divided into low, medium and high temperature FCs. A further distinction can be made according to the type of electrolyte used. Common FCs are the solid oxide fuel cell (SOFC) and the proton exchange membrane fuel cell (PEMFC). [9]. The way an FC system can be operated is characterized by its properties, which vary between the different FC types: For FCs with low to medium operating temperature, the preheating time before operation can be reduced. This avoids complex thermal management systems and enables a short start-up time. The high energy density of hydrogen results in a lower system weight compared to battery systems.

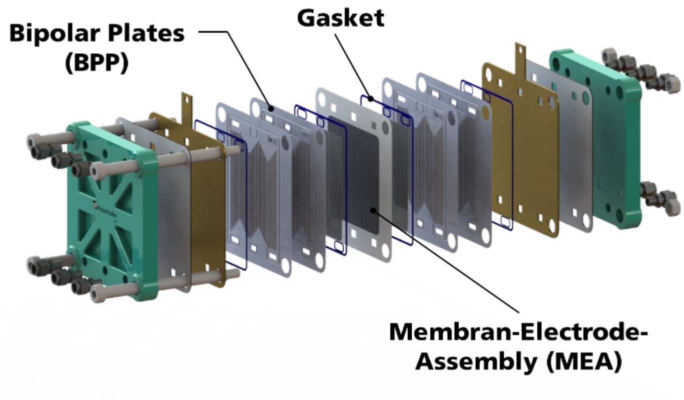

Figure 2: Schematic representation of a PEMFC stack (Source: Fraunhofer IPT)

As an example of low-temperature fuel cells, the structure of the PEMFC is shown in Figure 2. A single cell consists of a bipolar plate (BPP), the gasket, the gas diffusion layer (GDL) and the membrane electrode assembly (MEA). The MEA consists of two electrodes, each functionalized with a catalyst, and a polymer electrolyte membrane (PEM) in the center of the cell [10]. These cells are stacked in hundreds to obtain the desired power output. Such cell stacks are referred to as stacks.

A major advantage of hydrogen technologies is the possibility to enable sector coupling, e.g. between industry, mobility and the energy sector. In recent years, automotive manufacturers and suppliers have increasingly considered FCs as a possible technology for powering commercial vehicles. Three key technical requirements are shaping their application in transportation:

- Short start-up time (low operating temperature)
- High efficiency
- High volumetric and gravimetric power density [11], [12].

Due to their discontinuous operation capability, PEMFCs are the most suitable type of FC for transportation and mobility applications [13]-[16]. The PEMFC can be designed for different applications depending on the technical requirements, such as output power or geometric size. This enables the use of FCs as a solution for zero-emission mobility for cars as well as for trucks and buses. FCEVs enable high ranges with short refueling times of just a few minutes.

The necessary green hydrogen may be produced by electrochemical splitting of water into Hydrogen and Oxygen through the so-called electrolysis. Employing this reaction inside an **electrolyzer (EL)**, it consists of several hundred cells, which are enclosed by end plates [17]. As with FCs, there are different designs of ELs, which can be broadly divided into alkaline electrolyzers (AEL), polymer electrolyte electrolyzers (PEMEL), and solid oxide electrolyzers (SOEL). Analogous to the fuel cell, the PEMEL is also the most dynamic system with a high energy density and may be used with dynamic energy sources like sun or wind. In addition, the production processes of PEMEL and PEMFC are comparable. The PEMEL is therefore discussed below. The cells essentially consist of identical components: the bipolar plate (BPP), the membrane electrode assembly (MEA), the gaskets and the porous transport layer which correspond to the GDL of FCs. [18]. Technoeconomic considerations have shown that especially the catalyst-coated membrane (CCM) as part of the MEA accounts for a large share of the total stack cost and has a large scaling potential. Depending on the system performance and production technologies, the price can be reduced by a factor of six by increasing the number of pieces [17], [19]. The two main functions of CCM in PEM systems are the acceleration of the chemical reaction by noble metals (catalysts) on the electrodes and the conduction of hydrogen protons through the membrane.

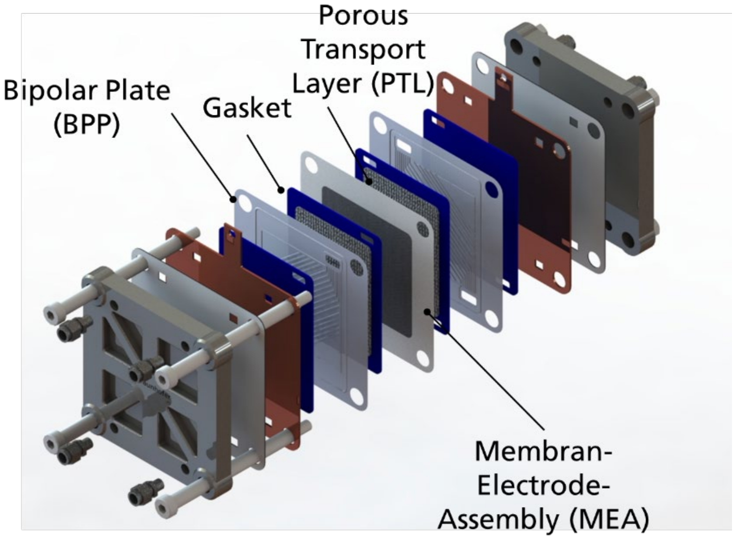

Figure 3: Schematic representation of a PEMEL stack

2 Production of batteries and H_2 systems

The production of energy storage devices has experienced rapid development in recent years. In particular, the production of LIBs has become a major industry. More and more companies are also focusing their portfolio on the development and production of PEM-FCs. Electrolyzers are currently still produced in smaller quantities but are on the threshold of high-rate production.

To achieve high efficiency and quality, manufacturers of energy storage systems rely on automation and digitization in production. Production processes are optimized and automated through the use of robots, artificial intelligence and novel process technologies.

Sustainability is also an important aspect in the production of energy storage devices, as these products often require a high input of materials and resources. A growing number manufacturers are turning to environmentally friendly materials and production processes to reduce their ecological footprint. One example from LIB production are the efforts to minimize the use of rare and expensive raw materials such as cobalt or platinum and replace them with more sustainable alternatives.

In addition, the scalability of production plays a major role. Manufacturers must be able to adapt production quickly and effectively to increasing demand and changing or evolving products in order to be successful in the market. In addition to the production of energy storage systems for the vehicle and transport sector, the stationary storage of renewable energies is also becoming increasingly important.

2.1 State of the art - battery production

Although battery production is already highly scaled, new trends have to be taken into account, which raise challenges with regards to flexibility of production processes. On the one hand, new product generations and changes within the prevailing battery systems require changes in the entire production chain, such as all-solid-state batteries (ASSB) or sodium-ion cells. On the other hand, future requirements for economic efficiency and sustainability require innovations within the currently dominant production processes for LIBs. These changes create market opportunities for mechanical and special machine engineering companies. By 2030, battery production capacity in Europe is forecast to grow by more than 1300 GWh. (see Figure 4) [7].

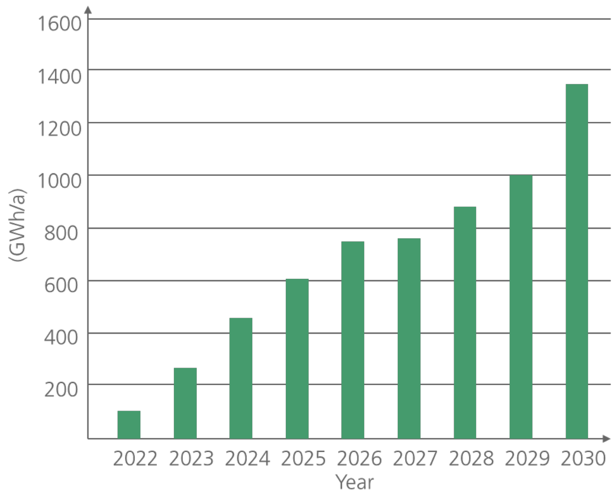

Figure 4: Projected growth of battery production capacity in Europe according to [7]

The fabrication of LIB cells is a complex process consisting of three superordinate interacting steps: electrode fabrication, cell assembly, and cell finishing [20]. While electrode fabrication and cell finishing are almost independent of the cell format, the process steps within cell assembly differ for the three relevant cell formats: pouch cell, cylindrical cell, and prismatic cell. The established production steps of a pouch cell are described below as an example.

Electrode production begins with mixing the active materials with conductive carbon black, solvents, binders and additives according to the cell recipe. Usually, this process is carried out in batches rather than continuously. The coating materials are then applied to the collector foils (anode: copper; cathode: aluminum) in a wet process using a coating tool such as a slot die or a doctor blade. To remove the solvents, the coated electrode foils are passed through a drying oven. Coating and drying are closely linked and often integrated in one machine. In the subsequent process step of calendering, the coated copper and aluminum foils are compacted over rotating pairs of rollers to set the desired porosity. Slitting describes a separeting process in which a wide electrode coil (mother roll) is divided into several smaller electrode coils (daughter rolls). To remove the residual moisture, the electrode strips are rolled onto a special material carrier and fed into a vacuum furnace. During cutting, the individual electrodes of the anode and cathode foils are separated from the coils, e.g. with the aid of a punching tool.

The subsequent stacking process requires high positioning accuracy. At the same time, damage during handling must be avoided. The doublesided coated electrodes are stacked in the recurring sequence anode-separator-cathode-separator-anode-etc. The stacked collector sheets are then contacted with the cell tabs (e.g., by laser welding). Afterwards, the cell stack is inserted into the thermoformed aluminum foil and the pouch cell is sealed (e.g., by impulse sealing). After sealing, the cell is filled with liquid electrolyte, usually with a high-precision dispensing needle, while the cell is exposed to argon and vacuum in alternating mode. During cell finishing, in addition to the initial activation of the cell and the formation of the SEI layer, the final testing processes also take place. A summary overview of the production process is shown in Figure 5 [20]-[22].

After cell production, the cells can be packed into modules, which are then assembled into so-called packs. The packs are installed as components and must keep mechanical, thermal and chemical environmental influences away from the batteries. The long service life is often ensured by housings made of metal or fiber composites, which are fitted with a cover and corresponding seal.

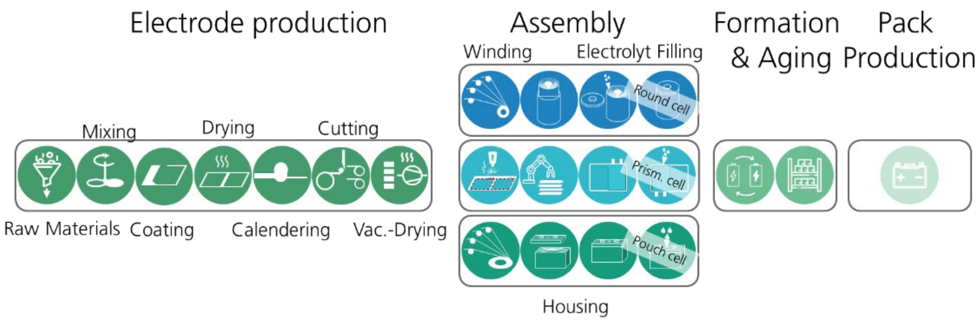

Figure 5: Overview of the production process of a LIB

Commercially available machines and line concepts Foto LIB production are very similar in terms of the sequence of processes and the technologies used. For example, each line is equipped with a classic convection dryer, which is by far the largest machine (~100 m) in the entire production line due to the high web speeds of up to 100 m/min and the required drying time of up to 1 min. Regardless of the space requirements, there are also enormous energy requirements. Within electrode production, drying can account for up to 50% of the total energy requirement.

In assembly, various technologies have become established that were already familiar from earlier automotive applications. Modules and packs are often encapsulated or glued together. Opening of the pack or replacement of the individual cells is therefore not possible. Thus, inline tests must be performed after the individual production steps and cannot take place collectively at the end of the production line.

In summary, battery production can be described as a high-scale manufacturing process that is already established in the automotive industry. However, many process steps show further innovation potential. The challenge is to determine the effect of process control on product properties and quality. This gives rise to a great need for production research to holistically optimize the entire value chain and streamline individual processes.

2.2 State of the art - H_2 systems

The production of PEMFC and PEMEL is not yet high-volume capable. The first automated lines for series production of PEMFC exist or are currently being set up in Europe, Asia and America. However, PEMEL production is still largely done in single or small batch production. As described in chapter 1, PEMFCs and PEMELs are similar in terms of their structure but can differ considerably in their dimensions. Production can be regarded as correspondingly synergetic. In contrast to FC, no clear or categorizable cell designs exist yet for ELs. A generic consideration of production chains is therefore only possible to a limited extent. Due to the lack of definition of technology and process sequence, there is a great opportunity for mechanical engineers to contribute their knowledge and influence the production of the future. PEMFC / PEMEL series production should be efficiently and sustainably planned and established from the beginning during the market peak. In the following, due to the non-scaled and inhomogeneous designs of PEMEL, the production technology of PEMFC is mainly discussed and PEMEL is only taken up in special cases. The expected number of units of PEMFC is significantly larger than for PEMEL, but the cells tend to be smaller than PEMEL.

There are four important process steps to consider for the fabrication of a PEMFC stack which consist of hundreds of individual cells (see Figure 6). These steps are the fabrication of the BPP, the fabrication of the MEA, the assembly of the gaskets and the repeated stacking of the different components.

Modern BPPs for mass production are made of 75-100 µm thick stainless steel or titanium sheets [23], [24]. The production line for BPP manufacturing must perform four process steps: Forming the flow field, cutting gas inlets, joining two half-plates, and coating the plates. The order of these steps may vary depending on the technologies used [23].

Figure 6: Photo of a metallic bipolar plate (Source: FCI Fuel Cell Industrialization GmbH)

The core of the MEA consists of the proton exchange membrane (PEM) and the catalyst layer (CL) applied on both sides. This subassembly is referred to as the MEA3L. The GDL lies on the outer surfaces of the CL and defines the MEA5L. In combination with the subgasket, the MEA7L is defined.

Figure 7: Photo of a MEA with half-laid GDL (light gray) on the CL (black) with reinforcement frame (white) (Source: FCI Fuel Cell Industrialization GmbH)

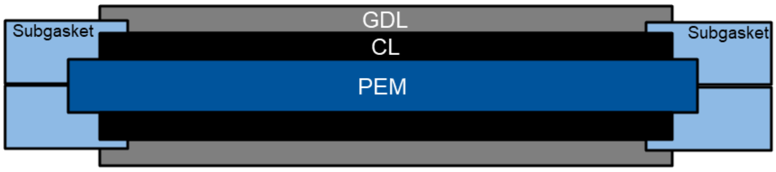

Figure 8: Schematic cross-section of an exemplary MEA (Source: FCI Fuel Cell Industrialization GmbH)

The PEM is a proton conducting PFSA membrane. The GDL usually consists of a carbon fiber substrate with a microporous layer. Both the PEM and the GDL are generally prefabricated and supplied as plates or coils. One of the most important processes is the deposition of the CL. There are three basic strategies for applying the catalyst and several technologies for the application process itself. Regardless of the catalyst application technology, different layers are hot pressed together to form the MEA7L assembly. In a final step, the MEA is cut into the desired size. [24]-[26].

According to the mentioned technologies and processes, some possible flows are shown in Figure 6 and divided into the two main steps already mentioned: BPP production and MEA7L production.

To make a gasket, the sealant can be applied to either the BPP or the MEA. The sealant must normally cure before the cell is assembled. A third option is to use a prefabricated inlay gasket, which is inserted between the MEA and BPP when the cell is assembled. BPP and MEA are alternately positioned on top of each other to build up the total stack.

Commercially available production systems or lines use continuous, indirect coating on a decal with subsequent transfer to the membrane. The decal is often coated with slot nozzles. A heatable calender is used for the transfer. Due to the properties of the interfaces, the transfer process takes a certain amount of time, resulting in a web speed of less than 1 m/min. The remaining layers are applied in roll-to-roll processes and can run faster than 1 m/min.

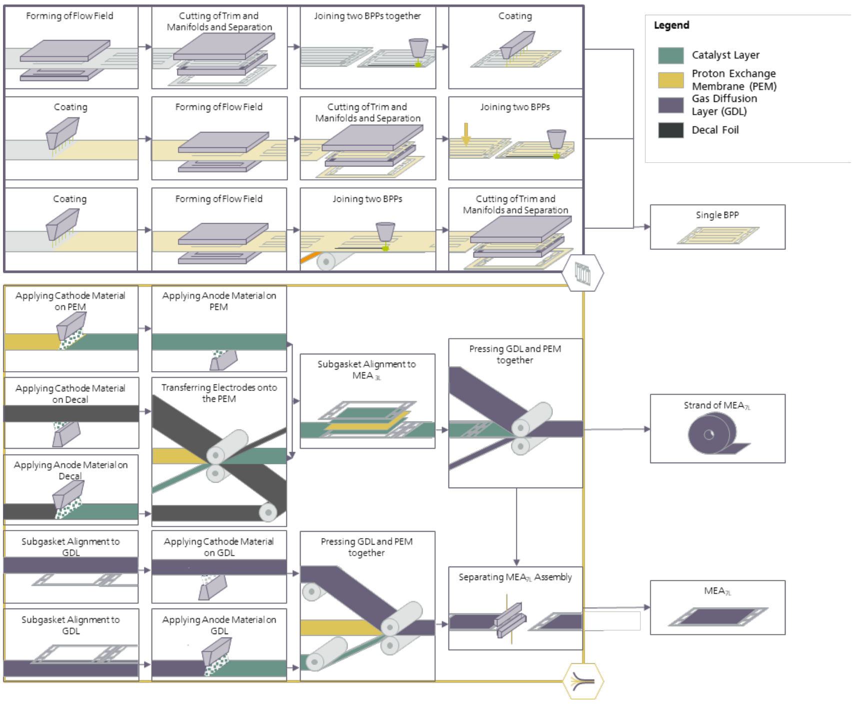

Figure 9: Process chain for the production of a PEMFC [27]

In summary, PEMFC and PEMEL production can be described as a hybrid manufacturing with elements of continuous and discrete production and complex supply chains. An example hybrid process chain is shown in Figure 9 is shown. The first large-scale plants are under construction, but the current demand can be met with small batches. In terms of process technology, some technologies such as hot pressing have been adopted from early development phase laboratory setups. Accordingly, it is difficult to scale the processes currently in use. Since both individual processes and interconnected production lines are currently being set up, there is a great demand for available technologies for scaling.

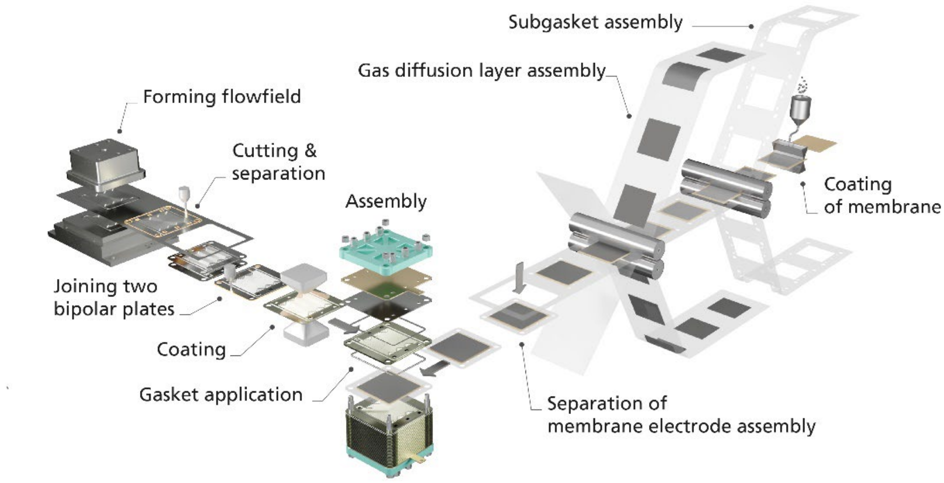

Figure 10: Example hybrid production chain for a PEMFC stack with discrete and continuous processes

In summary, energy storage production is achieved by means of hybrid process chains with discrete and continuous processes. These often have innovation potential through an improvement of the technology or disruptive adaptations of the production machines. This transformation must be data-driven in order to achieve an efficient transformation in terms of productivity and quality and thus be able to produce in a more resource-efficient and sustainable manner.

3 Improvements to individual processes and production lines

In addition to considering process chains, individual processes are important in the context of overall manufacturing. For example, the improvement of specific processes can reduce the cycle time or the energy requirement of the entire line. The improvement of processes with data-based optimization methods is discussed in chapter 4. As described in Chapter 2, in battery production, drying and the time-consuming assembly or sealing of the pack have low efficiency. In the production of H2 systems, there is a lack of fast production processes for CCM production with direct coating. These processes are examined in more detail below and technological improvements are proposed.

3.1 Optimization of convection drying

Electrodes for batteries are nowadays produced in a vast majority of applications on a large industrial scale in tandem coating line (Figure 11). The high acquisition costs (CAPEX) of such machinery are often the focus of attention today when considering economic efficiency. In many cases, insufficient attention is paid to the often-considerable follow-up costs during operation. After only a few years, these operating costs (OPEX) exceed the costs for the pure acquisition. Therefore, a comprehensive consideration as well as optimization of the total costs (TCO) must take place.

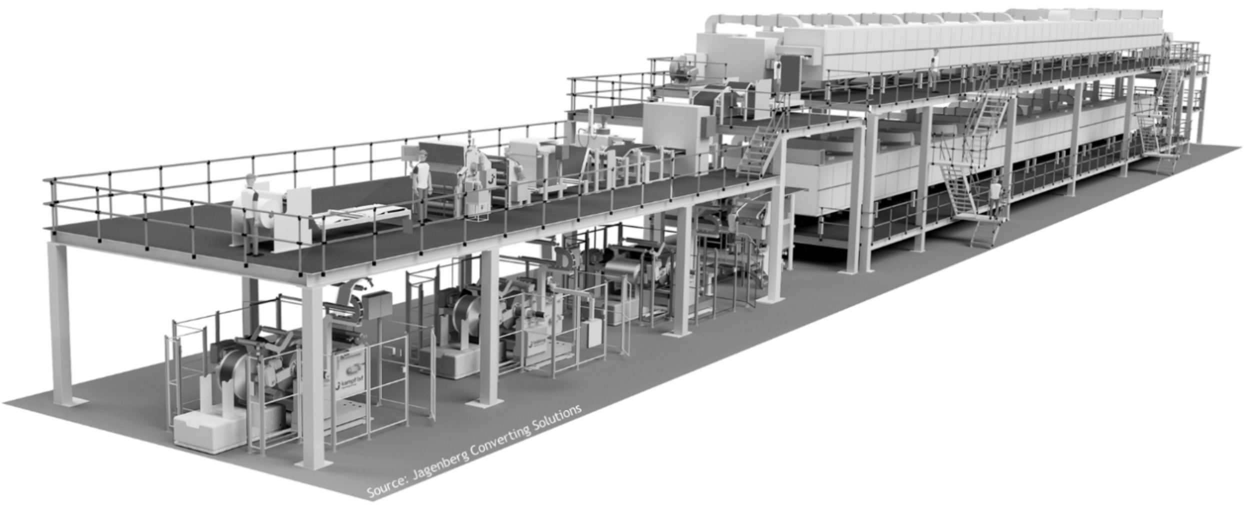

Figure 11: Tandem coating line for battery electrodes (Source: Jagenberg Converting Solutions)

Convection drying is still a common method for drying coated electrodes (anode and cathode). Here, the drying process decisively defines the line speed as well as the energy consumption. Up to 50 % of the energy required by such a system is used for drying the coating.

Suspended convection dryers are often used to dry wet layers. The double-sided coated collector foils are exposed to warm gas streams on both sides, which leads to the drying of the layers. Since the heat only reaches the upper layers of the electrode material and is thus dried from the outside in, the process takes a long time. Both the heat transfer into the material and the mass transfer out of the porous layer mean that conventional convection dryers require a lot of space and power and generate a large waste heat flow. Current convection ovens often use fossil resources such as gas or oil to generate the required process heat.

In order to increase the economic efficiency and user-friendliness of the coating and drying lines, the optimization of the dryers is of decisive importance. Measures can be taken here with regard to the process parameters, e.g. by increasing the solvent loading, and through optimized air management. Here, up to 30% of CAPEX can be saved, e.g. in installation, insulation as well as recovery systems. Optimized process parameters can also reduce the energy costs (OPEX) of the dryer by up to 50%.

The air flow and air management within the dryer not only influence the quality of the electrode, but also define to a decisive extent the speed at which the plant can be operated stably. The very thin material (often < 10 µm) is extremely sensitive, which can lead to wrinkling and subsequently to unstable process conditions in the plant. Very high web speeds can be achieved by special nozzles, in which an air stream drives rolls by a Ven-turi effect (Figure 12). On the one hand, this increases the productivity of the line (OPEX) and, on the other hand, costs for roll drives (CAPEX) can be significantly reduced.

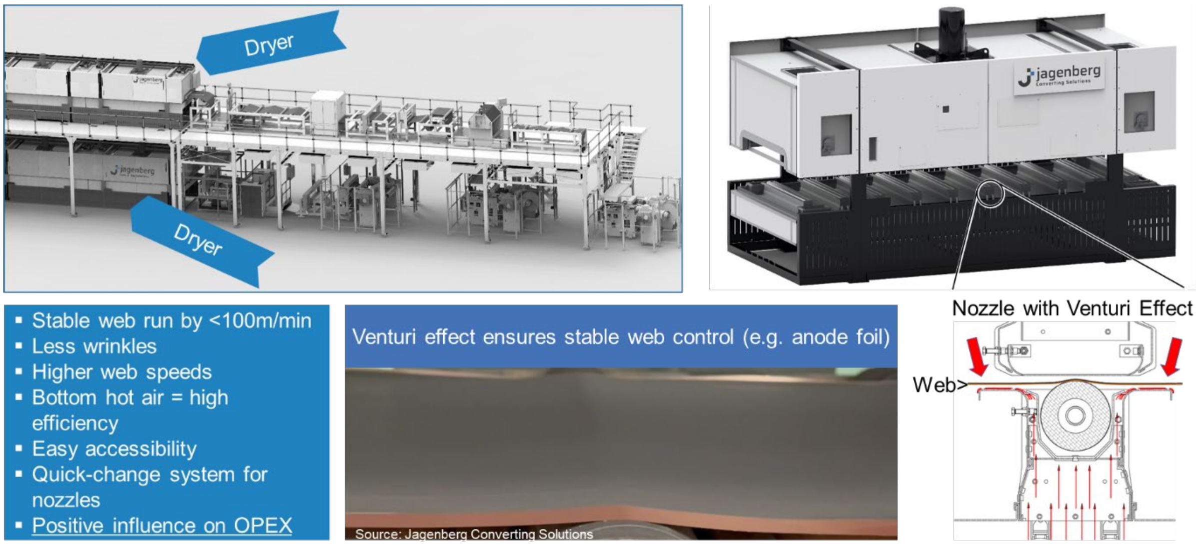

Figure 12: Energy-efficient dryer for high belt speeds (Source: Jagenberg Converting Solutions)

In many cases, the selection of the supposedly optimal process parameters is based on experience or empirical determinations.

The use of virtual prototypes during development, e.g. in the form of CFD simulations or physics-based interactive simulations, helps to optimize components and also to determine the most optimal manufacturing process parameters possible in advance of commissioning.

3.2 Novel radiation-based drying processes

Disruptive changes in the drying process are represented by near-infrared (NIR) and laser drying. In both processes, heat input is provided by electromagnetic waves, which enable more efficient drying by reaching deeper layers and thus drying the coating homogeneously in a location-specific manner. Drying time or energy consumption can be reduced by up to 90%. In addition, only about 10 % of the previous installation space is required.

Infrared (IR) dryers are already used in various industries such as the paper and textile industry, plastics processing and food production. Drying by IR is based on the heating of the material by the radiation of infrared light. The infrared radiation is absorbed by atomic bonds in the material, causing them to vibrate. Near infrared light (NIR) with a wavelength peak at 800 nm, can contribute a particularly large amount of energy. These oscillations result in heat, which is conducted accordingly into the surrounding material. Since polar solvents, especially water, are excellent absorbers of near-infrared radiation, the drying rate is increased by NIR dryers, thus shortening the drying time compared to conventional drying methods. NIR dryers are also capable of drying a wide range of materials quickly and uniformly without affecting the quality of the material. They can therefore dry batteries and fuel cell electrodes with slight adjustments.

A major problem of radiation-based drying is the formation of a boundary layer on the substrate, since the evaporated solvent is not transported away collectively, but diffuses only due to concentration gradients. This inhibits the escape of further solvents. One way to remove this layer is to apply a defined gas flow along the surface, as shown in Figure 13 shown.

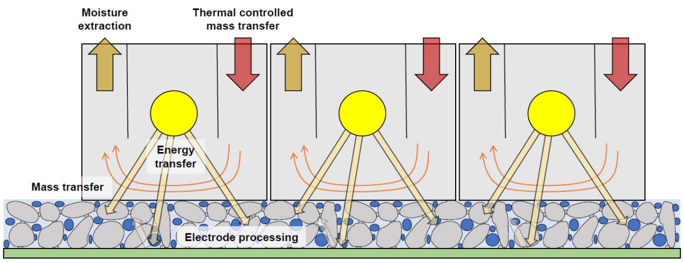

Figure 13: Schematic diagram of three NIR dryers connected in series with radiation source and gas flow (Source: Adphos Innovative Technologies GmbH)

NIR dryers are used in current production lines only in conjunction with convection ovens. To illustrate the performance, the energy consumption of three dryers was compared by Adphos. The results can be found in Table 1. As a reference, a water-based anode slurry was applied to a substrate. The wet film thickness was ~ 200µm, the dry film thickness was 120 µm and the film width was 200mm. Drying was performed in continuous mode at 3 m/min.

Compared to laser drying, NIR can achieve higher cost savings because near-infrared lamps are cheaper than lasers. In addition, NIR currently has a higher level of development. Validation as a stand-alone solution without another drying process in a large-scale production environment is still pending. Data is essential for the efficient use and validation of NIR dryers. For example, product data such as absorption and slurry composition can provide significant indication of thermal and mechanical behavior during drying, enabling more efficient production. Production data during drying coupled with a high-resolution track and trace concept enable targeted traceability of production defects and can also improve the drying strategy. Both data origins ultimately enable quality parameters to be inferred from the product and production data in order to be able to decide on subsequent operations already during production.

Table 1: Experimental comparison of different drying technologies (Source: Adphos Innovative Technologies GmbH)

Anode Slurry	**Device version**	**Total energy consumption**
Hot air convection thermally heated air + electric ventilation	95 kW 8 kW	103 kWh/h 100 % (ref.)
Medium wave IR electrical power with Lamp cooling, no ventilation	38 kW + 2 kW	38 kWh/h 37 %
NIR drying system electrical power (energy transmission) + electrical power (Exhaust ventilation)	10 kW 3 kW	13 kWh/h 13 %

3.3 Efficient assembly of battery packs

Battery cells in vehicles must be assembled in modules and then or directly in packs. One widely used process uses jointed-arm robots to apply sealing compounds analogous to existing bonding processes in the automotive industry. The disadvantage of such bonding solutions is cycle time and reversibility. With regard to the cycle time, it should be noted that so-called beads, which are dispensed by a robot-guided dispenser, first have to foam up and can then be brought into contact with the second joining partner. Adhesive systems of this type meet the requirement for sealing against environmental influences such as foreign liquids or particles. Once the lid has been applied, the pack cannot be opened again, which can be a hindrance to end-of-line testing but also to recycling processes. Any data collected in production but also in the life cycle cannot be used as efficiently as possible in this way.

One approach to enable both faster cycle times and reopening can be the application of adhesive tapes with accurate production machines. Establishing such a material solution requires the cooperation of all stakeholders involved. Collaboration between product and material development as well as process and production automation can unleash synergy effects. For example, the company tesa SE has developed a new, flexible adhesive application system that, in addition to reliable, clean, and automated sealing of battery packs, also enables the battery pack to be reworked without any problems [28]. The acrylic foam-based material requires no curing times and can be processed easily and automatically. Vulkan Technic GmbH developed the appropriate application concept for this purpose. Liebherr- Verzahntechnik GmbH supplied the proof-of-concept for the implementation of the entire production process as general contractor. An automated applicator changeover concept reduces CAPEX for the basic machines as well as setup times for material changes (OPEX). For example, a liquid adhesive dispenser can be operated on the same basic equipment as the adhesive tape applicator. In addition, new options for product flow design are created. On the one hand, reaction times of the foamed liquid adhesive are eliminated. On the other hand, reworking outside the production line and spatial and temporal decoupling of the application process and its downstream processes can be implemented. In addition to economic advantages, production can thus also be more sustainable [28]. Data play a decisive role in the new closure technology. By a double lapping of the tape at the start or end point, sufficient closure is ensured. The length of the overlap and the distance between the two tapes can be optimized by analyzing product and production data.

3.4 Direct coating of CCMs for PEMFCs and PEMELs

One of the first processes in PEMFC/-EL production is the application of the electrodes or catalytic layers (CL) to the membrane. In small series production, this layer, which is a few µm thick, is first coated onto a decal and dried, and then transferred to the membrane in a hot press. The process is similar to the laboratory processes used to develop CCMs. The advantage of this process is the easier handling of the membrane, as it can warp (up to 30%) due to contact with solvents, which can be eliminated by drying the CL beforehand. The disadvantage is the long duration of the process. In development laboratories, the stationary process can take between 60 and 300 seconds. This process is mimicked in current production lines with a heated calender or roll carpet and with preheating zones. Due to the line contact area of the calender, two-dimensional pressing is not possible. The web speed must therefore be in the low single-digit m/min range and represents an obstacle to possible further scaling. Direct coating of the membrane is independent of the hot-pressing process and can thus make use of all available scaling options. A machine-side approach to suppress the curvature of the membrane during coating is presented below.

The reason for the distortion of the membrane on contact with organic solvents is the material from which the membrane is made. It is made of an ionomer, typically a sulfonated fluoropolymer copolymer based on tetrafluoroethylene, and is thus impermeable to electrons. Hydrogen ions diffuse through the PEM and react with oxygen to form water. Ionic conductivity is provided by a polymer network filled with water and organic solvents. When the solvents are exchanged, the polymer network changes and so does the macrostructure of the membrane. The CL usually consists of carbon particles with platinum and a certain amount of the same ionomer, which is also used in the PEM. In this way, the ionomer, carbon particles and platinum form an interface where ionization takes place. For wet coating technologies, the solids are usually dispersed in alcohols.

Since the MEA is a critical component that limits the lifetime of a PEMFC stack, high quality components are mandatory. In addition, the MEA has a significant impact on the efficiency and stability of an FC [29], [30]. A relevant subcomponent for efficiency and cost is the catalyst used. The level of catalyst loading directly affects the goal of increasing the interface (active surface area) between the catalyst, ionomer, and electrically conducting catalyst support (see Figure 14). A larger amount of active catalyst can optimize power density and durability, but also leads to an increase in material cost. Maximizing the available catalyst is therefore of great interest and can be influenced by different types of production technologies. In most applications of PEMFCs, platinum is used as the catalyst material.

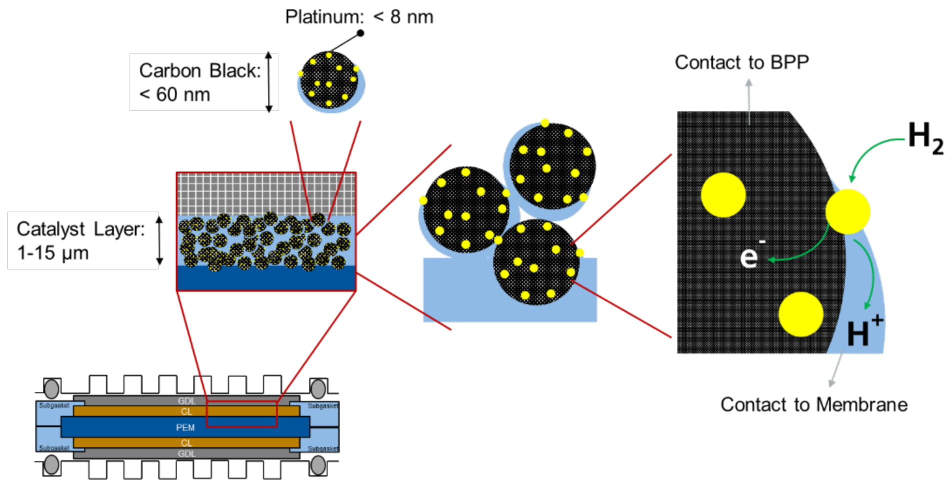

Figure 14: Structure of the layers of a MEA and transport of reactants (Source: Fraunhofer IPT)

In the following, a machine concept for direct coating with inkjet is presented, which addresses the described problem.

Regardless of the coating substrate (decal/membrane), it must be determined whether the substrate is to be built up continuously (continuous) or with uncoated areas (intermittent). Schematically, both processes are shown in Figure 15. Continuous coating allows a steady-state process using conventional technologies such as the slot die coating. Dis-continuous coating needs more flexible coating technologies without start-up and stop delays, such as the slot die process. Depending on the design of the MEA (see. Figure 8), continuous coating results in the need for singulation and discrete handling onto the subgasket. Part of the catalyst is obscured by the subgasket and thus does not contribute to the electrochemical reaction. Intermittently coated membranes offer advantages in terms of catalyst utilization.

Figure 15: Illustration of continuous and intermittent coating

A suitable coating technology with enough flexibility with regards to intermittent coating could be inkjet. In addition, coating by inkjet offers greater flexibility for the coating geometry since slot nozzles can only coat at right angles.

Intermittent coating on decals requires complex layer detection on the decal and subsequent synchronization of three webs to position the CLs on top of each other over the entire area. Direct membrane coating, on the other hand, only requires the membrane to be placed in the correct position and coated at the correct time. Product-specific control of the coating also increases catalyst efficiency and avoids potential scaling bottlenecks.

However, direct coating requires strong two-dimensional fixation of the membrane to avoid any upheavals. Proven workpiece supports are vacuum tables with vacuum holes smaller than 0.5 mm in diameter. Vacuum tables, usually used for discontinuous processes, can be converted into a highly scalable machine concept in two main ways. A vacuum roller can be used or a vacuum belt can be installed. The advantages and disadvantages of the two approaches are discussed below.

A **vacuum roller** is a roller with holes made on the running surface to draw vacuum. Holes with diameters smaller than 0.5 mm are difficult to make in a rotationally symmetrical body by conventional means. Therefore, there are approaches to manufacture vacuum rollers by means of metallic 3D printing.

The coating process by Inkjet usually takes place with solids content of a few percent. The viscosity and yield point are therefore usually low. If possible, the coating should be applied to a roller on a plane parallel to the floor to avoid tiling. However, since layers of up to 20 µm have to be applied in the PEMFC and PEMEL area, the inkjet process consists of several print heads or several nozzles in succession, depending on the web width and speed. To ensure an equal distance to the roller, the print head would therefore have to be curved. Drying should take place immediately after coating, so that distortion effects of the membrane can be minimized. According to the web direction, the dryer would be arranged at an angle with respect to the bottom, which is not a problem. More problematic is the unequal distance of the substrate to the dryer due to the curvature of the vacuum roll. One way to compensate for this effect is to dry after detachment from the roll. In preliminary tests, however, it was observed that drying without fixing the membrane leads to significant distortions of the membrane. Drying on the roll is therefore essential. A final problem arises for near-series prototypical production. Placing membranes on the roll in the sheet process involves a certain complexity. In addition, the time in which the area to be printed has to be detected depends on the speed but even more on the roll diameter. If the detection were done in advance, the subsequent suction could result in a deviation.

In contrast, the welded **vacuum belt** can drift significantly and exact belt tracking is only possible after intensive characterization. If the drift can be controlled, there are some advantages in using a vacuum strip. The production of steel sheets with holes in the diameter of 0.5 mm can be realized by etching. The orientation of the belt is always horizontal, so when coating with low viscosity inks, only the web speed needs to be considered, not gravity. The coating and drying always has the same distance to the samples to be dried and the time to detect the layers depends on web speed and belt length. Another disadvantage of the vacuum belt is that strong vacuum requires strong motors to overcome the friction of the belt on the underlying vacuum plates.

In summary, rollers are much easier to handle, especially for high vacuum applications, but may need fast sensor technology to detect layers. Vacuum belts, on the other hand, are to be favored when flexible quantities and lower vacuum quantities are required.

In addition to the speed of the sensor technology for detecting the coatings, the **coating technology** is a decisive feature that influences the efficient coating. State of the art for coatings of membranes for PEMFC and PEMEL in scaled productions are slot dies. This technology is also used in battery production and is well researched. The advantage of the slot die is the fairly simple design and thus low CAPEX. The disadvantage is the behavior during start-up and when the process runs out or when coating is not to be done over a wide area. Thus, slot nozzles need a certain time after start-up until the coating is reproducible. Intermittent coating can be achieved by start/stop of the feed, but to the disadvantage of the edges of the coating. The reason for the sluggish behavior is the physics behind the slot die. A meniscus forms in front of the nozzle, which allows a uniform coating. If the ink flow stops, the meniscus degrades and the coating quality changes.

At the beginning of a new coat, the meniscus must be rebuilt accordingly. There have been slot dies equipped with piezo actuators for a few years to address this problem. In this way, the distance between the lips of the nozzle can be controlled and thus the meniscus can be specifically controlled.

In addition to the complex control of slot nozzles for intermittent coatings, the alignment in axial and transverse direction must also be considered for efficient coating. Accordingly, the slot die would have to have two actuators by which it could rmove orthogonally to the web direction and rotate around its center. An alternative with fewer actuators is inkjet technology. Due to its high number of individual print nozzles, it is possible to generate a shape that is matched to the previously determined field, analogous to inkjet table printers. This means that area-wide coating is conceivable by means of digital control. Conversion to other dimensions or even geometries is correspondingly simple. This capability makes it possible to flexibly produce new product designs. One disadvantage of inkjet coating is the relatively low solids content of the inks of just a few percent and the associated necessary evaporation of the solvent. NIR drying techniques could address this challenge.

4 Development of next generation production lines

In the production of energy storage devices, the rethinking of existing production lines is gaining more and more attraction. Many energy storage system manufacturers face the challenge of aligning their production with increasing demand and new product types. One option is to optimize production lines so that they are flexible enough to respond quickly to changes in demand. The implementation of automation and digitalization, as well as the use of environmentally friendly materials, can help to reduce production costs and improve the sustainability of production. In addition to improving individual technologies, new production methods can also be researched and introduced to increase the efficiency and quality of energy storage production. However, rethinking existing production lines often requires investment in research and development as well as new technologies and equipment to remain competitive in the long term.

4.1 Novel battery production

In battery production, the importance of sustainability and economic efficiency is increasing. There are significant differences in these criteria within the various technologies of modern battery cell production. For an exemplary battery factory in Germany with a battery production capacity of 7 GWh/a, it is analyzed in Figure 16 analyzes the distribution of energy consumption and the corresponding GHG emissions as well as manufacturing costs over the individual process steps of cell production. However, it should be noted that this analysis does not take into account other energy consumers such as drying rooms or battery handling, and that natural gas and electricity can be substituted to some extent. Thus, the resulting carbon footprint depends on the underlying electricity mix and natural gas composition. [21], [22], [31] .

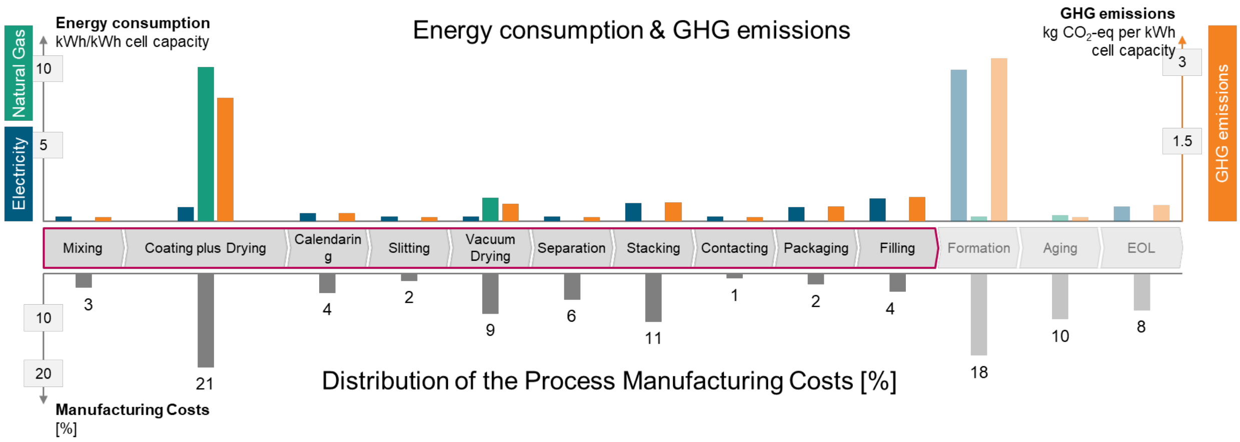

Figure 16: Analysis of process steps in terms of energy consumption, greenhouse gas emissions and manufacturing costs taken from [22]

When considering the criteria of costs and energy consumption, three manufacturing steps within electrode production and assembly stand out: coating, drying (incl. vacuum drying) and stacking.

The close connection between coating and drying is a major cost driver in battery manufacturing and is often integrated into a common facility. About 21% of the manufacturing costs are allocated to this process step, as it has a high energy consumption (~10 kWh/kWh cell capacity when using natural gas, which is more than 80% of the total gas consumption). In addition, a lot of space is required for the long drying ovens. Solvent removal in particular requires a lot of energy and needs to be reduced in light of rising natural gas prices. Furthermore, vacuum drying adds 9% to manufacturing costs because it requires additional process heat to remove residual moisture. Within cell assembly, the stacking process is the largest cost driver due to its slow process speed (1 electrode/s) and high space requirements [6]. Currently, there is the disadvantage of a lack of flexibility in stacking. Existing stacking machines are only suitable for certain cell formats and sizes, making it difficult to adapt production. For this reason, there is a need for a continuous and flexible stacking process that accommodates changing cell designs and sizes [32].

Innovations can be divided into radical and incremental innovations. A radical innovation could be to avoid solvents in the material mix and instead switch to dry coating. Incremental innovations, on the other hand, could be aimed at optimizing the existing wet coating process, for example by improving the established convection drying process with laser or near-infrared drying. In terms of electrode manufacturing and cell assembly, the stacking process is the second largest cost driver. Currently, stacking is performed by discontinuous pick-and-place processes, which could still be optimized.

Figure 17 illustrates the effects of the innovations presented on upstream and downstream process steps and shows corresponding technology chains. It can be seen that the greatest impact is in the dry coating technology chain, which affects most downstream processes. In contrast, the optimized drying technology chain is only related to the drying process itself and can largely be carried out with the existing plant technology. The electrode manufacturing technology chains have the potential to be linked to the continuous stacking innovation.

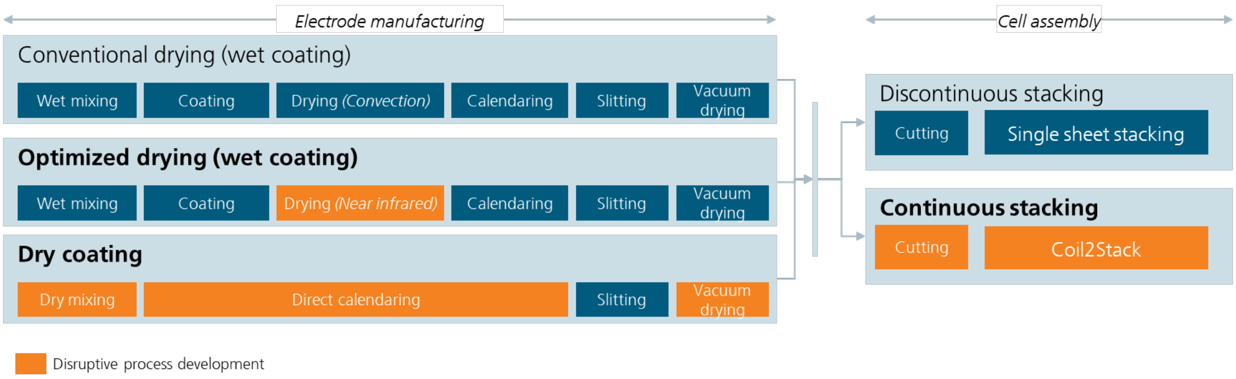

Figure 17: Derivation of future technology chain alternatives based on the technology innovations studied taken from [22]

Over the next 1-3 years, it will be necessary to conduct further research and development efforts for each of the technologies shown in Figure 17. In the long term (> 5 years), dry coating will provide undeniable benefits by significantly reducing costs and energy con-sumption. However, the medium-term (3-5 years) use of a particular technology chain depends on the progress of dry coating technologies. Since industrialization of dry coating is realistic in the long term, laser and near-infrared drying technologies may gain traction sooner because they are easier to integrate into existing equipment. Battery equipment suppliers should carefully monitor further developments in dry coating technology, whether or not they are suppliers of the technology, as it will fundamentally change battery cell production. For example, a convection oven manufacturer could face a potential decline in addressable market volume, even though demand for battery equipment in general is increasing. Equipment suppliers should therefore identify the impact of potential innovations along the process chain on their established technology and also explore and monitor new innovations in upstream and downstream processes [22]. Novel battery con-cepts require novel production concepts, since a change in cell chemistry or design al-ways means a change in production technology. Meanwhile, product and production data can be used to implement changes more efficiently and based on experience.

4.2 Future production of H_2 systems

With the emergence of the first large-scale productions, it is important to already look at the production of tomorrow and the day after tomorrow. Current productions use scaled processes from laboratory applications and make use of battery production technologies. The direct coating described is one way to increase efficiency and allow more flexibility. The choice of a coating technology has an impact on the final design and subsequent processes.

A possible production chain based on direct inkjet coating is described below. The focus in the machine selection should be on flexibility, synergetic production and resource effi-ciency. Due to the flexibility of Inkjet, both continuous and intermittent coating is possible.

After double-sided coating, the CCM coil must be slit and cut, ideally parallel to the applied CLs. Due to the flexibility or design of the CCMs and component-specific deviations, laser cutting is a suitable option. This technology allows each component to be specifically singulated. After coating, the CCM is double-sided bonded into subgaskets. These are self-adhesive thermoplastic films from which an opening for the CL has already been cut. Roll-to-roll positioning can be done either with the CCM coil or with individual CCMs. More resource efficient is the pick and place of a CCM onto 194th unwound subgasket. Then, in a second pick and place step, the second subgasket is placed and the MEA is rolled up again. In the last step, this MEA coil can be unwound again and the separated GDL can be placed in a pick and place step. This step must be performed twice.

With the process flow described, MEAs can be produced using two machinery. The first machine coats and dries the membrane (CCM production). The second machine consists of a vacuum belt with two Gantrys, which position the various products on the web. Thus, with appropriate sensor technology, the described processes "CCM on subgasket" and "MEA on GDL" can be mapped within one machine. Due to the small number of machines, matrix production of various products such as PEMEL and PEMFC is conceivable.

Innovations are also needed in the production of the metallic bipolar plates as the second central component in hydrogen systems to reduce costs and upscale production. Several materials can be considered as the base material for the metallic bipolar plates. In the state of the art, stainless steels and titanium materials are used in particular. Both materials are fundamentally formable, although titanium presents a greater challenge in this respect, but has a higher corrosion resistance. This factor is decisive in terms of the service life of the BPP. Stainless steel or, prospectively, aluminum can be advantageous in mobile applications due to their lower density and are also more cost-effective than titanium materials. There are basically two forward-looking process variants for high rate forming of bipolar plates. One is discrete and the other is continuous. Representatives of the discrete processes are the progressive die forming technology or the use of a transfer tool. Roll-to-roll forming can be described as continuous forming in this distinction since the base material moves continuously. The choice of the appropriate process depends strongly on the number of pieces to be produced, the design of the BPP, the base material and the application area or size.

Overall, the choice of process for manufacturing BPP is highly dependent on the characteristics of the specific component. Both discrete and continuous manufacturing processes have advantages and disadvantages, and the decision of which process to use should be carefully weighed to find the optimal production method for the specific BPP design. In addition, the effective combination of multiple forming principles has been insufficiently studied. Hybridization of forming may be another promising approach to develop the production technology for the future of BPP forming.

With increasing quantities of both BPPs and MEAs, the financial footprint of scrap and plant utilization increases, both aspects of what is known as Overall Equipment Effectiveness (OEE). OEE must be kept as high as possible, and data is a key enabler of this. Thus, the production lines being set up can take advantage of corresponding data-driven synergies right at the start of high-rate production of PEMFC and PEMEL and avoid development issues, the LIB production lines have faced. Data regarding PEMEL and PEMFC has the potential to reduce expensive raw materials such as iridium and platinum, lower the amount of flour-based polymers (PFAS) and enable predictive maintenance of the stacks.

4.3 The data value chain in energy storage production

The growing requirements for scalability and sustainability in energy storage system production also necessitates the use of data-driven optimization methods. This requires the implementation of reliable data value chains as well as a data pipeline, pre- and preparation processes, a targeted analysis of the data, a data management concept and the final application.

The data pipeline describes the entire path of the acquired data from the source, for example a sensor, through preprocessing steps to the data sink. Building on a database created in this way, various assistance and optimization systems can be developed. Digital twins offer a wide range of optimization possibilities in production. A product twin can support product development through simulations, facilitates the monitoring of product quality and enables traceability methods. Product lifecycle management (PLM), which is important in terms of sustainability, can also be implemented with a product twin. A plant twin, on the other hand, supports the optimization of the production process itself. With the help of predictive maintenance, wear and tear on plant components can be predicted. This enables early intervention, thus reducing downtime and avoiding possible damage to other components.

Furthermore, the knowledge gained from historical data of existing machinery can be applied to optimize novel processes and identify synergies. One challenge in implementing data pipelines is the heterogeneity of the plant landscape and the data to be collected. However, modern IoT platforms enable the integration of different data sources via common communication protocols. Edge computing can be used to clean up and synchronize the heterogeneous data before persistent storage.

5 Summary and conclusion

The production of energy storage systems is a dynamic market, which is essentially driven by the battery and fuel cell products. This results in considerable demands on the scalability and flexibility of the production technology used. Battery production has to adapt to new trends, which is difficult due to existing processes. There are changes in the entire production chain due to new product generations and changes within the prevailing battery systems. Market opportunities for machine suppliers are emerging as battery production in Europe is forecast to grow by more than 1300 GWh by 2030. LIB cell production consists of electrode manufacturing, cell assembly and cell finishing. Comparatively much energy is required for drying in electrode manufacturing. Innovations are possible in improving existing technology such as convection drying or disruptive developments such as NIR drying. Both technologies increase the drying rate, reducing dryer length and energy requirements. After cell production, the cells can be packaged into modules, which are then assembled into so-called packs. These are currently irreversibly bonded, which makes testing and recycling difficult. Innovative solutions are available here with tapes and their application, which enable sealed and reopenable packs.

In the manufacturing of LIBs, there is little synergy with the manufacturing of other cell formats or cell chemistries, leading to a great need for improvement in many process steps. However, there is great uncertainty regarding the impact of process changes on reliability and quality. Possible implications of improvements on subsequent production processes can be far-reaching. To remove this barrier to innovation, research is needed to rethink the complete value chain and streamline processes. Data-driven production optimization can be a tool for this.

The production of PEMFC and PEMEL is not yet high-volume capable. The first PEMFC lines are being built worldwide, while PEMELs are still largely produced manually. The production technology of PEMFCs and PEMELs is similar, but for PEMELs the cell designs are not very categorizable. PEMFC production involves four process steps: Fabrication of the BPP, the MEA, assembly of the seals, and repeated stacking of the various components. The demand for the systems can currently be met with small batches, but the processes currently in use are difficult to scale. There is a high demand for available technologies for scaling, as both individual processes and production lines are being built. One barrier to faster scaling is the need to transfer the catalytic layer from decals to the membrane. This is remedied by direct coating processes, which are additionally built into a flexible machine concept to enable synergetic energy storage systems production. Supplemented with flexible, continuously operable pick and place solutions, a platform for flexible MEA production can be created. With regard to BPP, a distinction can essentially be made between continuous and discontinuous processes. Both processes offer individual advantages and disadvantages, which have an implication for the subsequent use of the stack.

All in all, it can be seen that there are sufficient research approaches for improving existing production lines. The manufacturing industry must take up these solutions and build new types of production lines. Possible risks in terms of quality and reliability can be reduced by evaluations on existing machines and backed up by data. Only by further developing existing, purchased plant technology and using its own machine developments can the European industry play to its strengths and generate global added value.

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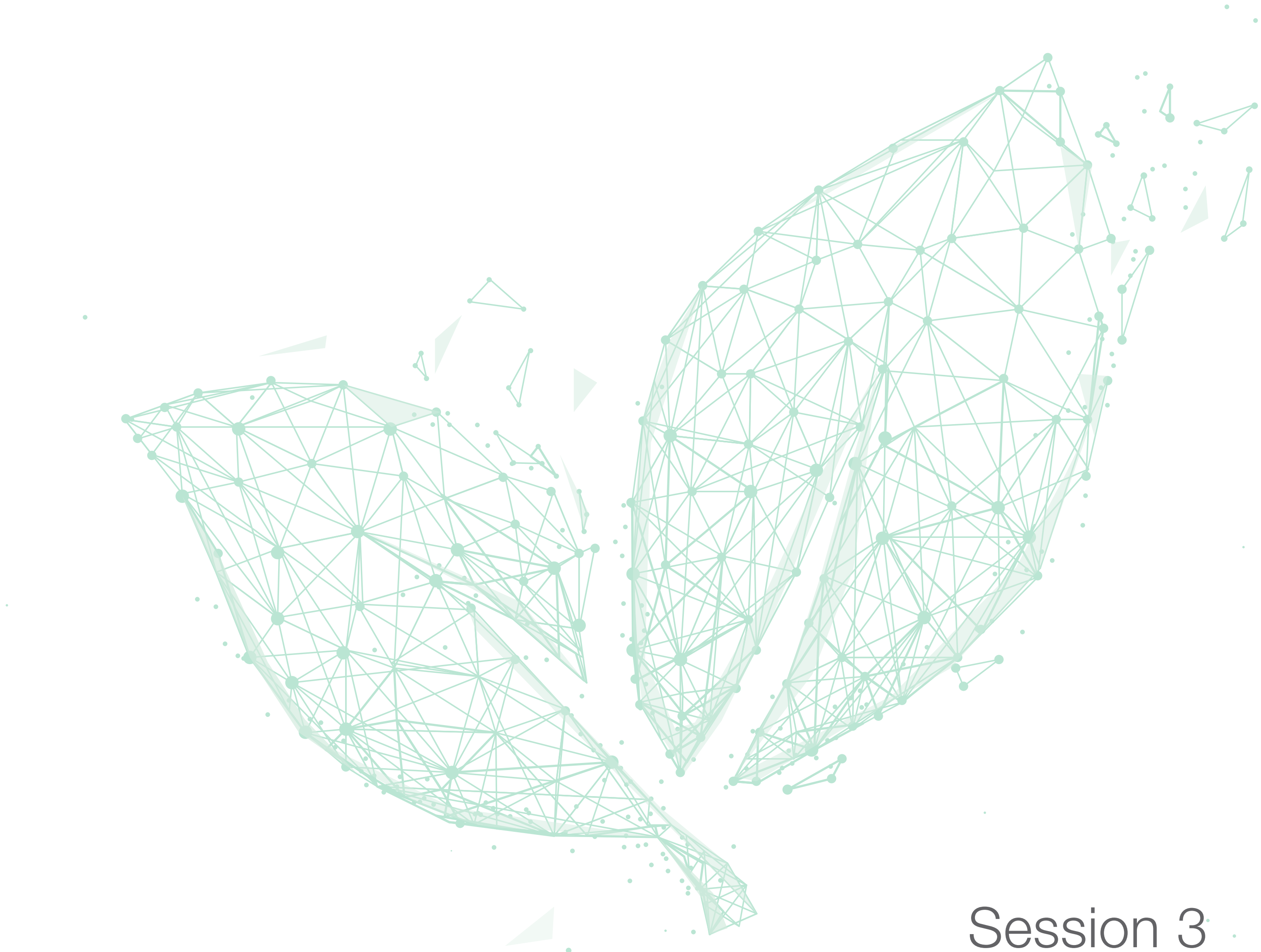

Session 3

Production-as-a-service

3.1 Sustainability in Production Lines

C. Brecher, M. Fey, M. Loba, O. Malinowski, J. Ochel, J. Schäfer, A. Steinert, M. Wittmann

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Abstract

Sustainability in Production Lines

Profound global change processes have intensified the demand for sustainable action. One key to successfully designing the sustainability transformation in production is to minimize the overall use of resources. Against this background, it will not only be necessary to establish resource-efficient manufacturing of products, but also to reduce the number of product means in circulation. By optimizing the utilization of the theoretical potential of product means currently in use, it will be possible to meet the current demand of products even with a reduced number of product means. In order to harmonize this basic sustainable idea with entrepreneurial interests, monetary incentives in the form of new business models must be created.

The formulated goals can be addressed in production lines when the following three approaches are pursued: more efficient use, extension of the use phase and circular economy of production means. A consistent and overarching availability of data and know-how along the entire life cycle makes it possible to evaluate sustainability holistically and identify well-founded optimization scenarios. AWK’23 presents concrete use cases that contribute to sustainable and at the same time future-proof production through different measures within the three approaches.

Keywords: resource minimization, efficiency increase, use phase, circulation, data availability

Kurzfassung

Nachhaltigkeit in Produktionslinien

Tiefgreifende globale Veränderungsprozesse haben die Forderung nach nachhaltigem Handeln verstärkt. Für eine erfolgreiche Gestaltung der Nachhaltigkeitstransformation in der Produktion liegt ein Schlüssel in der Minimierung des gesamtheitlichen Ressourceneinsatzes. Vor diesem Hintergrund wird es nicht nur erforderlich sein, eine ressourcenschonende Herstellung von Produkten zu etablieren, sondern auch die Anzahl eingesetzter Produktionsmitteln zu reduzieren. Diese Reduktion muss einhergehen mit der vollständigen Ausnutzung des theoretischen technischen Potentials, da sonst der erforderliche Bedarf an herzustellenden Gütern nicht mit einer reduzierten Anzahl an Produktionsmitteln gedeckt werden kann. Um diesen nachhaltigen Grundgedanken mit unternehmerischen Interessen zu harmonisieren, sind monetäre Anreize in Form neuer Geschäftsmodelle zu schaffen.

Die formulierten Zielsetzungen können in Produktionslinien adressiert werden, wenn folgende drei Ansätze verfolgt werden: Effizientere Nutzung, Verlängerung der Nutzungsphase und Kreislaufwirtschaft von Produktionsmitteln. Eine durchgängige und übergreifende Verfügbarkeit von Daten und Expertenwissen entlang des gesamten Lebenszyklus ermöglicht, die Nachhaltigkeit ganzheitlich zu bewerten und fundierte Optimierungsszenarien zu identifizieren. Das AWK‘23 präsentiert konkrete Anwendungsfälle, die durch unterschiedliche Maßnahmen innerhalb der drei Ansätze zu einer nachhaltigen und zugleich zukunftsfähigen Produktion beitragen.

Schlagwörter: Ressourcenminimierung, Effizienzsteigerung, Nutzungsphase, Kreislauf, Datenverfügbarkeit

1 Challenges of sustainable production lines

The economic success of manufacturing companies to date has been closely linked to maximum product sales and thus to a high use of resources in production. In the course of industrialization, this basic entrepreneurial understanding has led to overproduction enabling unit costs to be minimized and sales to be maximized. Due to this overproduction the demand for products is met, but in particular the socially reasonable demand is exceeded. Profound global change processes have intensified the demand for sustainable action in recent years.

The manufacturing industry is also confronted with the accompanying sustainability transformation along the FESG factors (Finance, Environmental, Social, Governance). Within a sustainable market economy, the manufacturing sector will have to face major challenges and develop a new basic understanding of sustainable corporate management. It will be necessary for companies to provide the socially reasonable demand for goods and services, e.g. mobility or manufacturing capacity, with a minimum use of resources and not to strive for the maximum possible product sales as in the past. Furthermore, a long-term goal of the sustainable market economy is to reduce the number of products in circulation. By optimizing the utilization of the theoretical potential of the products currently in use, the current demand can be met even with a reduced number of products.

With regard to production facilities, this means in concrete terms that products must be manufactured in a resource-saving manner and that a smaller number of production means must meet the demand. To sustainably achieve the formulated goals, it is necessary that production means are used more efficiently (1) and for longer (2). At the same time, production means must find a way into the circular economy at the end of a utilization cycle (3). (cf. Figure 1)

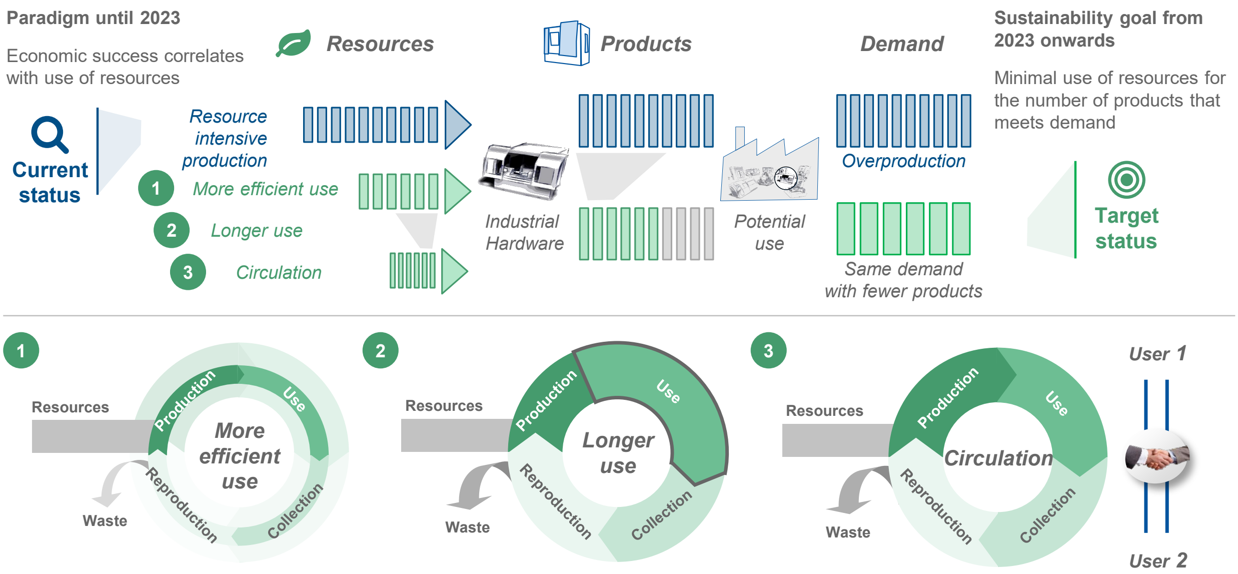

Figure 1: Status quo and scenarios for increasing the sustainability contribution

1.1 Existing approaches for the realization of sustainable production lines

AWK'23 builds on a long history of extensive research work, all of which dealt with the digitization of production technology in the broadest context. Many concepts and approaches have already been used in consumer goods for several years and often find their way into production technology with a certain delay. For example, parallels can be drawn with Google's route planning in recent years (cf. Figure 2). Starting with physical *model knowledge,* models were initially created that allow a priori predictions. In addition to the occurring process forces [1], [2] it is also possible to predict the service life of individual components [3]. Based on geometric models of the machine tool, early collision detections of the process to be performed are also possible [4]. From the manufacturing point of view, all these models enable an initial prediction of the manufacturing route to be taken, but do not represent stochastic effects and the resulting real state. In route planning, this model knowledge represents the road map. While it is possible to plan the route to be taken and predict the theoretical arrival time, it is not possible to account for traffic jams or road works. This requires *data-combined model approaches that* use live data. While this data is mobile phone or GPS data from vehicles in route planning, it is machine and quality data in production. By combining these data with domain-specific model knowledge, the real occurring process forces [5], [6] and the resulting loads on the tool and the machine components can be calculated. In practice, this enables in connection with a stiffness model and a material removal simulation a process-parallel monitoring of the part quality [7]. By attaching additional sensors, a further improvement of the prediction can be achieved [8]. Initially, these data-combined model approaches are only a direct analysis of the current state, which does not allow learning for process predictions [9]. For this purpose, (hybrid) *learning model approaches are* necessary which allow predictions based on historical events. With respect to route planning, this means incorporating history-based data, e.g. school vacations, regional sports and music events, or weather conditions. With regard to production planning, in addition to the prediction of wear of tools [10] or machine components [11], the more accurate prediction of process forces is also made possible [12]-[15]. Previous modeling approaches are mainly used to predict and optimize times, e.g. travel or process times. Future *sustainable modeling approaches,* on the other hand, must increasingly consider the solution path with a focus on environmental sustainability and minimize a use of the necessary resources. In concrete terms, this means minimizing CO_2 emissions per product manufacture or, analogously, per trip in route planning. In route planning, this is already being realized by Google. Route optimization is based on predicted CO_2 emissions. The fastest and shortest route is not necessarily the most environmentally friendly. Factors that influence this balance are the number and size of the gradients and the number of stops required, e.g. by traffic lights. In order to transfer this approach to production technology, machines and their manufacturing processes must be able to be evaluated ecologically in relation to one another and information for optimization must be available across the board. Only then the most sustainable production route can be selected.

1.2 Target values of sustainable production lines

A well-founded evaluation of environmental sustainability requires an analysis of the entire life cycle of a production line. The life cycle includes the sections raw material extraction, production, transport, use, waste disposal and recycling. The consistent availability of relevant data in all sections is the only way to identify the relevant drivers of resource consumption and to reveal the greatest potential for optimization. In the following, the article will focus the machine tool as an essential part of a production line. Studies in recent years have shown that a large part of the environmental impact of machine tools is caused during the use phase (94 – 99 %). Here, electrical energy contributes the largest share (99 %). [16] Accordingly, the energy conversion in the use phase is the relevant driver of resource consumption during the life cycle of a machine tool. For minimizing the use of resources, a more efficient use of the machine tool is of particular importance.

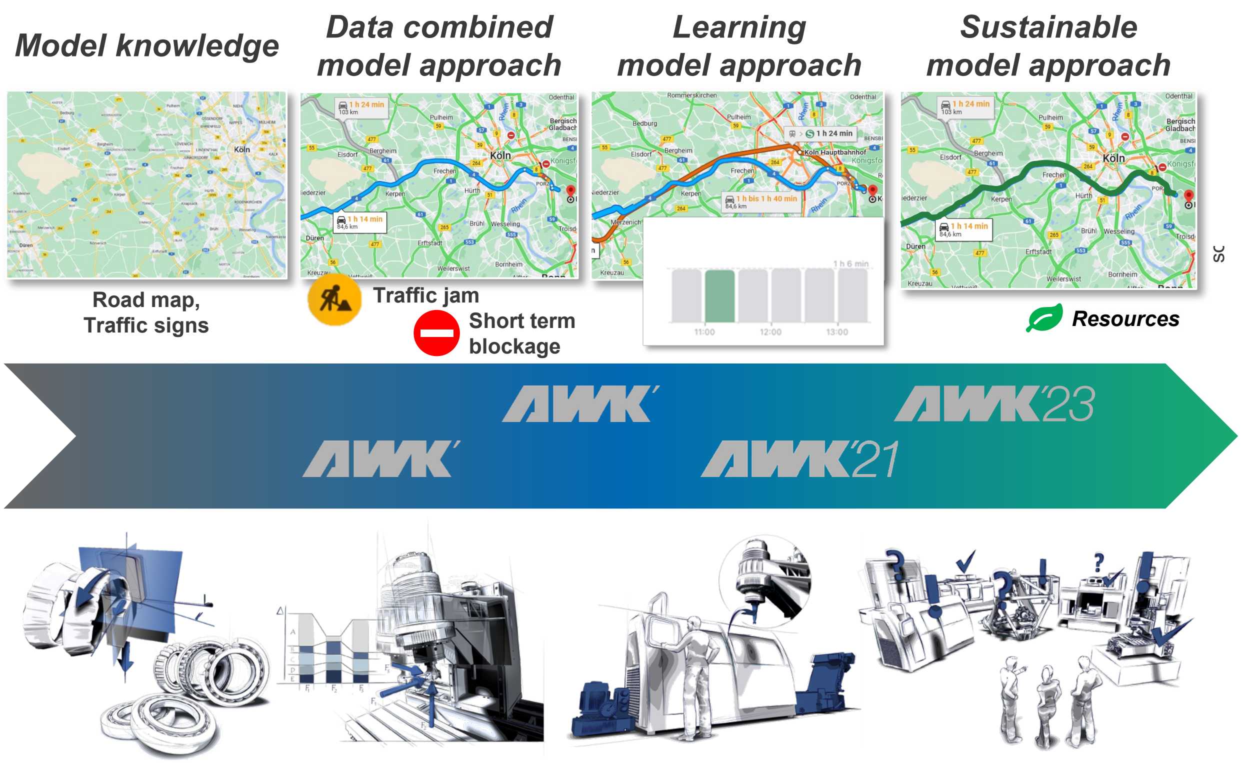

Figure 2: Analogies between route and production planning

Consequently, it makes sense to consider the power consumption of a machine tool over time during the use phase in order to break down the energy consumption of the machine tool according to its components and operating states and to derive concrete optimization measures.

In Figure 3 an example of the power consumption of a machine tool in productive operation is shown. The diagram shows the percentage shares of the main and auxiliary units of the machine relative to the overall power consumption. The main units are components that are directly involved in the process execution and the value-added process. These include the main spindle, the feed axes and the control. Auxiliary units, on the other hand, are systems that have a process-supporting function. For example, cooling system, cooling lubricant preparation and supply, and hydraulic system can be assigned here. [17], [18] In the lower part of the figure, the power consumption of the main and auxiliary units is illustrated schematically for different time periods during the use phase of a machine. The power consumption during the warm-up phase before starting machining, the productive operation and the entire use phase until machine failure, here caused by a spindle failure, can be seen. During the use phase of a machine tool, different types of energy consumption occur. The consumption can be divided into fixed and variable portions. The fixed energy portion is independent of the process and is defined as the base load. This base load is due to the auxiliary units. The variable portion, on the other hand, is dependent on the process. Variable consumption is mainly due to the main units.

Figure 3 shows that the auxiliary units account for a significant part of the energy consumption during the use phase of a machine tool. The largest consumers are primarily cooling lubricant supply, cooling system and hydraulic system. Two goals can be derived for a holistic optimization of the auxiliary units: The use of energy-efficient systems and the demand-oriented use of energy-efficient systems. In order to reduce the process-independent base load of the auxiliary units, the use of energy-optimized systems is necessary. The next step is to design these systems adaptively to enable a demand-oriented usage.

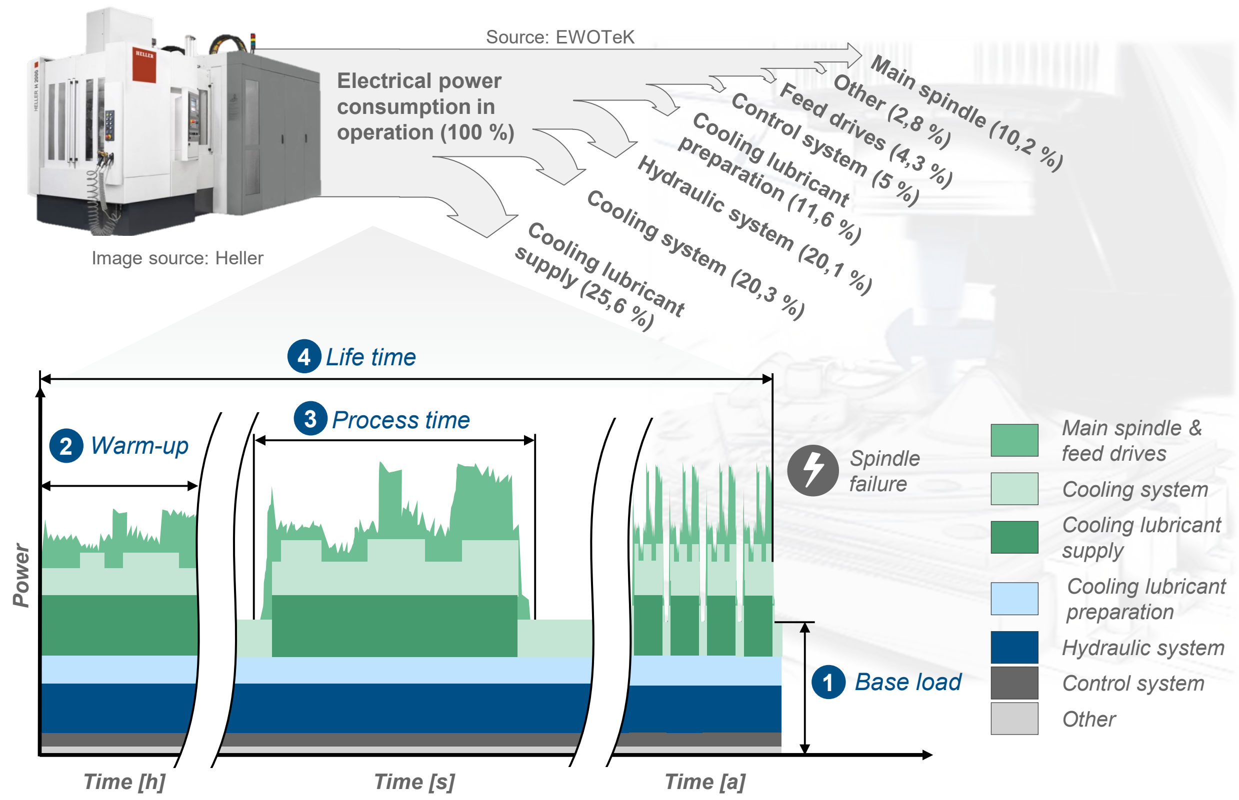

Figure 3: Power consumption of a machine tool in productive operation according to [17] and optimization approaches along a use phase

Taking into account further parameters for the overall optimization of the use of resources, the third target value is the minimization of the process time. This shortens the operating phase and thus the energy consumption per component of the main and auxiliary units. Studies in recent years have shown (cf. Table 1) that the energy consumption for the main units such as spindle or feed axes can increase due to a reduction in process time, but at the same time the energy consumption of the base load decreases to a significantly greater extent. [17]-[20]

The final goal is to maximize the service life of machines and its relevant components. The focus here is primarily on wear components such as drive systems or the main spindle, whose failure has to be avoided. At this point, expert knowledge is necessary for an accurate prediction of condition and service life depending on the operating parameters. This also makes it easier for components to find their way into the circular economy at the end of a use phase, since conditions of components are known more precisely and less damage or failure occurs.

When analyzing and evaluating the energy consumption of a machine tool during the use phase, four target values can be summarized for minimizing the energy consumption per component and thus for increasing the sustainability of machine tools (cf. Figure 3 below):

Target 1: Use of energy-efficient auxiliary units (chapter 0)
Target 2: Demand-oriented use of energy-efficient auxiliary units (chapter 3)
Target 3: Minimization of process time (chapter 0)
Target 4: Extension of the use phase (chapter 0)

The implementation of the four target values can result in further secondary effects that increase sustainability. For example, with demand-oriented use of the auxiliary units, optimized temperature management can minimize the workshop air conditioning that was previously required. The reduction of thermal fluctuations during operation also increases machine accuracy, so that waste due to quality defects is reduced. As a result of higher productivity through minimization of process time, it is possible to save on production lines in a next step. The reduced machine park also requires less workshop air conditioning.

All targets and possible resulting effects have not only an ecological but also an economic benefit for manufacturing companies, so that the realization of these targets leads to a competitive advantage for companies. The above-mentioned targets can contribute to sustainable and at the same time future-proof production.

2 Reduction of the base load of auxiliary units

By using energy-efficient auxiliary units, a reduction in the fixed, process-independent base load can be achieved (cf. Figure 4). The development and use of such systems to reduce resource consumption have been extensively researched in recent years. As early as 2011, AWK presented measures to optimize the energy efficiency of these systems and was thus a pioneer in the design of green production. Against the background of a shortage of raw materials and rising energy prices, the goal of increasing resource efficiency was primarily economically motivated. Efficient use of the resources, such as energy, raw material or cooling lubricant, could achieve a direct increase in profitability. However, resource efficiency was not the final target value with regard to which production was optimized, which is why many research results have not yet found their way into industry.

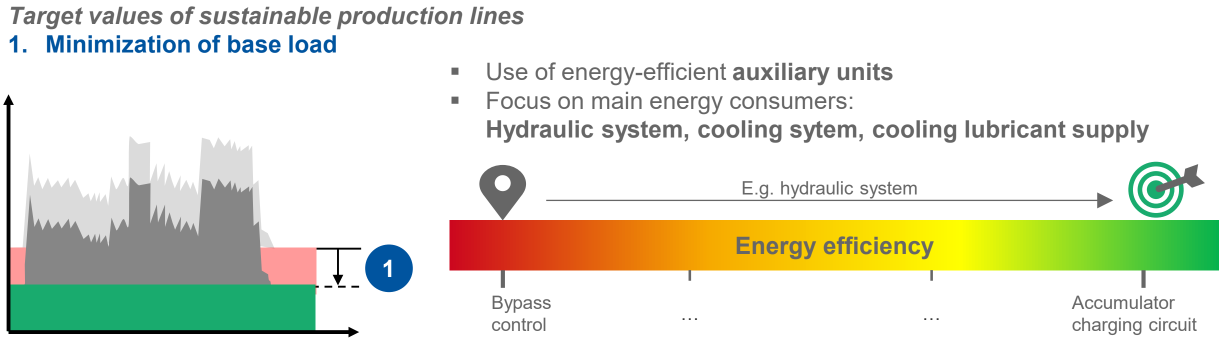

Figure 4: Minimizing the base load as a target value of sustainable production lines

As a result of the increased demands for sustainable action in recent years, ecological sustainability is now developing into a central evaluation point in industry. The already available optimization proposals and measures for reducing the base load of auxiliary units open up the possibility of directly exploiting energy-saving potential and significantly minimizing energy consumption in production lines when implemented on a broad scale. Results from various research studies and projects [17]-[20] prove that the realization of optimization scenarios for auxiliary units on different machine tools leads to large energy savings (cf. Table 1). For cooling system, hydraulic system and cooling lubricant supply, some of these more energy-efficient solutions compared to the standard system are presented below as examples. These solutions can still be implemented on machines already in use. Additional costs associated with these solutions are amortized by the savings in energy costs.

Table 1: Energy optimization of machine tools [18]

				Optimized		
Project	***Total consumption***	***Main units***	***Auxiliary units***	***Total consumption***	***Main units***	***Auxiliary units***
EWOTeK [17]	6.25 kWh	19 % ~1.19 kWh	81 % ~5.06 kWh	4.38 kWh	24 % ~1.05 kWh	76 % ~3.33 kWh
Maxiem [19]	0.78 kWh	14 % ~0.11 kWh	86 % ~0.67 kWh	0.38 kWh	29 % ~0.11 kWh	71 % ~0.27 kWh
NCPlus [20]	22.3 kWh	23 % ~5.13 kWh	77 % ~17.17 kWh	15.6 kWh	37 % ~5.77 kWh	63 % ~9.83 kWh

Hydraulics

For cost reasons, hydraulic systems with a fixed pump and fixed motor are frequently used today. The pump permanently provides a constant volume and the motor is permanently operated at a constant speed. Consequently, the power consumption of these hydraulic units is constant over the entire machining process, even though a hydraulic function is often performed only briefly and sometimes with a long time lag. In order to be able to convey variable volume flows, the unit is extended by a bypass. Via the bypass, some of the supplied hydraulic fluid then flows back into the tank unused. During the pressure maintenance function, when there is no volume flow required, the entire volume flow is returned unused. More efficient hydraulic systems are systems with a variable pump and constantly operating motor, with rotational speed control or with accumulator charging circuit. These systems make it possible to reduce the required power to maintain a constant operating pressure during the pressure-holding function. Optimized hydraulic units that operate according to the principle of the accumulator charging circuit can even reduce the power requirement to zero during the pressure-holding function and thus represent the most energy-efficient systems. Such hydraulic units consist of a pump, pressure accumulator and accumulator charging valve. During partial or no-load phases, the pressure accumulator can be filled by the pump. When the accumulator is fully charged, the pump switches to idle mode or shuts down completely and the energy supply of the hydraulic system is taken over by the pressure accumulator. During the pressure-holding function, this allows the motor and pump to be switched off completely.

Cooling

The main components of a cooling unit are the compressor, pump and fan, whereby the dominant power consumption of the cooling system is found in the compressor. In order to realize the large energy saving potential, the energy efficiency of cooling units with different compressor designs must be evaluated. In addition to the energy efficiency of a cooling unit, the accuracy of the temperature control of the cooling fluid is of central importance as well in order to meet accuracy requirements for the process. A control strategy could be, for example, to control the flow temperature of the cooling fluid with a certain hysteresis. The required precision of the machining process defines the size of the hysteresis. Energy-efficient units are those with an intermittent compressor (two-point control). Compressor and fan operate at the nominal operating point until the minimum hysteresis is reached. Then they switch off until the maximum hysteresis is reached again. Meanwhile, the pump runs continuously at the nominal point. In high-precision machining processes with low hysteresis, for example, a larger tank volume of cooling fluid must be used due to the limited number of permitted switching operations of the compressor. However, in order to still meet the requirements for a compact cooling unit, systems with a hot-gas bypass compressor are often used. This compressor consistently exhibits its maximum power consumption. In order to dissipate excess cooling capacity when required, the compressed, hot refrigerant is injected after the compressor via a bypass ahead of the evaporator. In this way, cooling capacity is dissipated and can be continuously regulated. To counter the poor energy efficiency of the hot-gas bypass method and use a compact cooling system at the same time, cooling units with frequency-controlled and digital-scroll compressors are to be preferred.

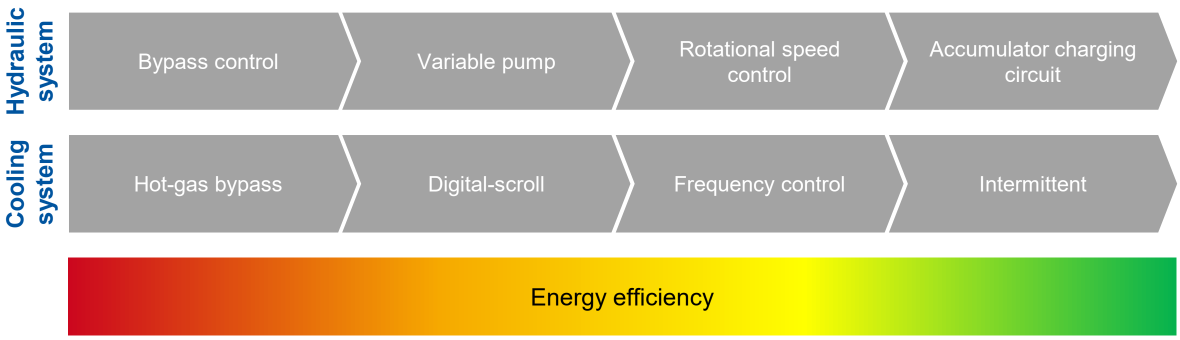

Figure 5: Different hydraulic and cooling systems and their energy efficiency according to [21]

Cooling lubricant supply

In addition to cooling and hydraulic systems, the cooling lubricant supply is one of the primary electrical consumers. In order to reduce the energy consumption of the pumps in use, a demand-oriented media supply can be effective. In the area of cooling lubricant supply, systems with bypass control are still used in some machine tools already in use. These systems are oversized for many operating states of the machine and are inefficient in terms of energy. The reason for this is that a machine is designed for the required volume of cooling lubricant at maximum demand. During the majority of the machining time, however, there are lower requirements and consequently a lower demand for cooling lubricant. In this case, the majority of the cooling lubricant flows back into the tank unused via the bypass and heat is unnecessarily introduced into the cooling lubricant. In this case, the energy consumption of the pump is independent of the process and the operating state of the machine [22]. In order to exploit the high energy saving potential, pressure-controlled, variable-speed pumps can be used. The supplied volume flow is determined by the pump speed, which is set by a frequency converter. Thus, only the coolant volume required for the application is provided.

3 Demand-oriented use of auxiliary units

The reduction of the base load based on energy optimization of auxiliary units has no direct impact on the production process. In a subsequent step, it is conceivable to optimize the operating phase of the corresponding units. In contrast to base load minimization measures in this area have a direct impact on the production process. The operating parameters of auxiliary units are therefore not only possible manipulated variables for increasing efficiency, but are also among the central manipulated variables for influencing machine operation. Optimization of the operating behavior of auxiliary units can therefore only take place on the basis of a holistic balancing. This involves solving an optimization problem, since a reduction in electrical power consumption is generally associated with reduced performance and thus reduced functional performance. Since a large number of unpredictable boundary conditions can influence a manufacturing process, an a priori design is usually not possible. Instead, the ability to react flexibly and, above all, immediately to changing boundary conditions is a central building block in the context of optimization. Against this background, the design of intelligent, adaptive auxiliary units can be formulated as an enabler to solve the conflict between energy consumption, productivity and quality.

The example of active cooling systems for machine tools is a good illustration of this concept. In modern plants, this auxiliary unit has two central tasks:

1. Cooling of electric drives to maximize power density
2. Temperature control of structural components to minimize thermo-elastic deformations

Today's cutting performance would be inconceivable without the use of active cooling systems, for example in the main spindle (1.). At the same time, selective tempering ensures that required part tolerances can be maintained even in high-productivity operation (2.). For this purpose, the cooling system of a machine tool, which consists of several circuits, is usually supplied by a central pump. By operating in two-point control, the temperature of the cooling fluid moves between a lower and upper limit. The entire system becomes active when the main drives are switched on and operates independently of the actual machine utilization. The consequences of this operating mode, which is comparatively simple despite its central importance, are high electrical power consumption of the cooling system on the one hand and further high thermo-elastically induced part faults on the other hand. To address this problem, long warm-up phases are planned in the industrial environment, especially in the case of critical machining operations, in order to bring the machine structure close to a thermally stable operating window. During these warm-up phases, no productive operation takes place and although the aim is to heat up the structure, the active cooling system runs at full load due to the static operating principle described above. Warm-up phases in this form are thus energy-intensive and inhibit productivity (cf. Figure 6).

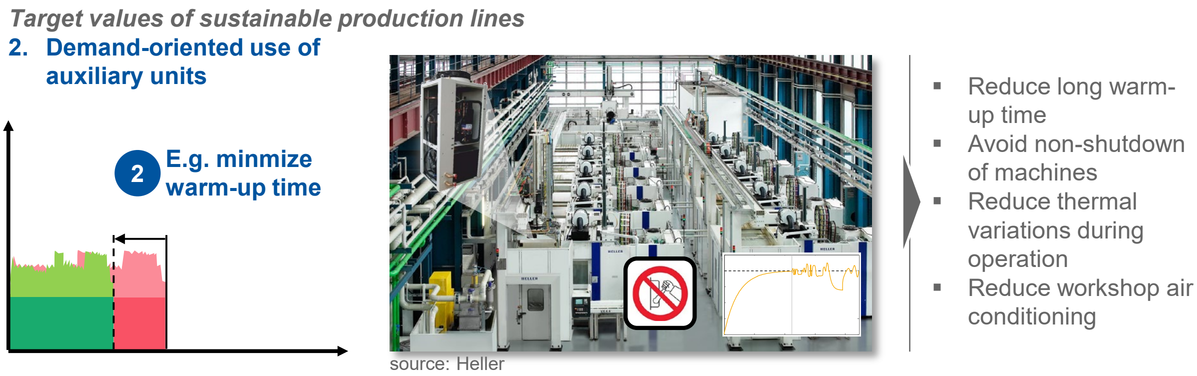

Figure 6: Demand-oriented use of auxiliary units as a target value for sustainable production lines

From the aforementioned grievances, the following goals can be derived for active cooling systems to address the optimization problem of productivity, quality and energy use.

> *Goal 1:* Reduction of warm-up phases through targeted heating of the structure (**productivity**)
>
> *Goal 2:* Increase machining accuracy by compensating thermal variations during the operating phase (**quality**)
>
> *Goal 3:* Reduction of energy consumption through demand-driven operation (**energy use**)

Figure 7 shows the three goals at the temperature level and the electrical power consumption of the machine.

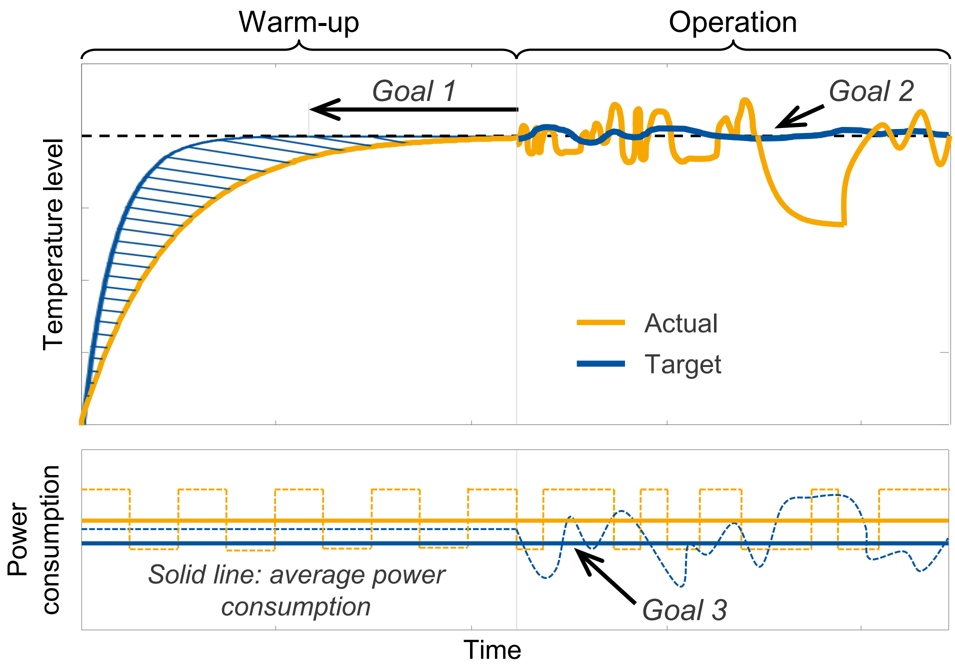

Figure 7: Target values for optimizing the operating phase of active cooling systems

The functionality required to meet these goals, i.e. to be able to react adaptively and intelligently to changing boundary conditions, is a basic idea from control engineering.

Following the multidimensional goal, the controlled variable results from several components. For the goals 1 and 2 the structure temperature of a machine tool can be defined as representative. An actively controlled structure temperature can, in combination with the appropriate cooling unit, enable a fast warm-up by targeted heating. In addition, demand-oriented cooling based on the structural temperature of the machine tool can enable stabilization of the thermal state during operation. Thermal stability then manifests itself in reduced thermo-elastic displacements, which has a positive effect on machining accuracy. For goal 3, the electrical power consumption can be defined as a controlled variable to be minimized, resulting in an overall multi-variable control with two controlled variables. As manipulated variables the cooling parameters must be mentioned, whereby a machine tool ideally has individually controllable cooling circuits so that, in addition to a temporal adaptation to the actual demand, a spatial adaptation of the cooling power can take place as well.

Against the background of comparatively high thermal time constants, the system model forms another important component of the control strategy. The system model provides the ability to predict future thermal developments and electrical power consumption as a function of the operating parameters. As soon as the effects of thermal phenomena manifest themselves in the form of an undesired displacement at the tool center point, quick counter-regulation is practically no longer possible due to the time constants mentioned. Instead, measures must already be initiated before the actual effect is felt in practice. The necessary "look-ahead" is achieved with the aid of this system model, which can be used to determine both the structure temperature and the electrical power consumption as relevant control variables as a function of thermal loads and effective cooling parameters.

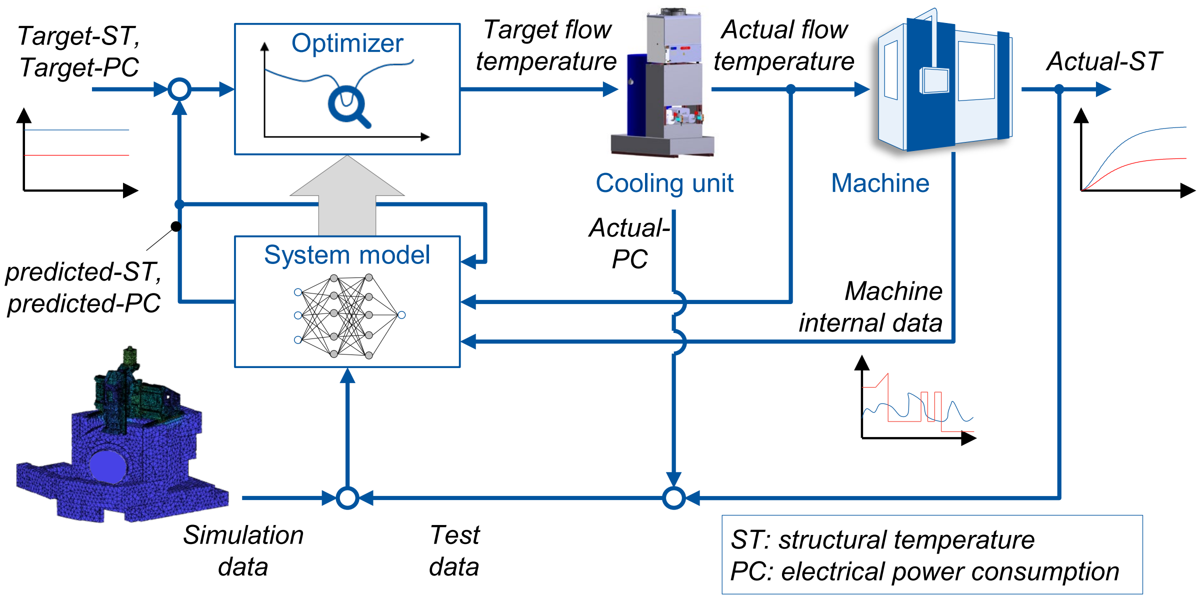

Figure 8: Structure of the model predictive multivariable controller

The resulting architecture of a model predictive control (MPC) is shown in Figure 8 and is implemented on a 5-axis machining center at Laboratory for Machine Tools and Production Engineering WZL. The current thermal loads are recorded using internal machine data such as spindle speed or torque-forming current in electric drives. The system model is then able to convert this data into a predicted actual structural temperature and the electrical power consumption of the cooling unit. The system model is an artificial neural network that has been trained a priori using simulation and experimental data. This combination of data to form a training base has the advantage that large data sets can be generated comparatively cheaply. Especially against the background of long test times, a good compromise between effort and reward can be found. The control variables predicted with the aid of the system model are compared with the reference variables. The control deviations are used in an optimizer to define new cooling parameters in such a way that the sum of the control deviations is minimized with currently acting load data.

A newly developed cooling unit is used to implement the target flow temperatures of the cooling circuits determined by the control system as optimum manipulated variables. The cooling unit enables the control of each cooling circuit with individual cooling parameters. From a hot and cold water tank, the required volume flow can be combined via a controllable mixer in such a way that the respective desired flow temperature is realized. Volume flow-controlled centrifugal pumps (cf. Figure 9) convey the cooling fluid through the cir-cuits. Since the hot water tank is designed as a stratified storage tank (not shown), the returning water stratifies according to the hydrostatic buoyancy. Returned hot water from electric drives can thus be used for heating structural components during warm-up phases, so that maximum energy efficiency is achieved.

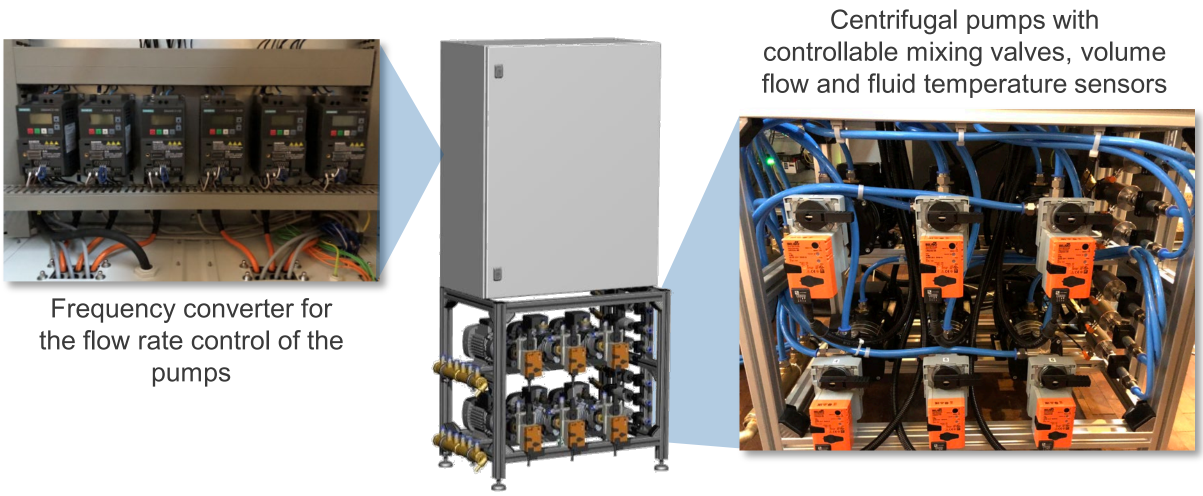

Figure 9: Representation of the external cooling unit for supplying the individual cooling circuits

The presented approach for the MPC of the active cooling systems could already be suc-cessfully implemented and tested on a main spindle. Figure 10 shows in the upper area that a stepwise increase in speed was carried out during a test run. With the help of the system model embedded in the optimizer, a target flow temperature for the jacket cooling was determined during the operating phase, with the help of which the temperature of the motor and the front fixed bearing were to be kept constant as controlled variables. It can be seen that the cooling unit is able to implement the target as far as possible, although a variation occurs in the course of the actual flow temperature. Due to the thermal inertia, this variation is no longer included in the temperature curves (cf. Figure 10 below). In the lower diagram, in addition to the curves optimized with the aid of the control system, the curves with conventional cooling strategy are also included, which contain successive increases corresponding to the speed steps. Three main results were achieved by imple-menting the MPC:

1. Within the first 500 seconds of the test run, a significantly accelerated warm-up to a higher, thermally more favorable temperature level takes place. The upper diagram shows that comparatively warm water is used for this. In this range, the active cooling system heats the structure.
2. During operation, the adaptivity of the cooling system ensures homogenization, expressed by significantly more constant temperature profiles. In addition to a reduction in thermo-elastic displacements, critical components such as the spindle bearings can thus operate permanently at an efficient and low-wear operating point.
3. In the range of the last 750 seconds, the spindle stands still and thus simulates an interruption of production. With conventional cooling, this causes an immediate drop in temperature. In the controlled system, this effect can be compensated for to a significant extent, so that production can continue with consistent quality after the end of the downtime.

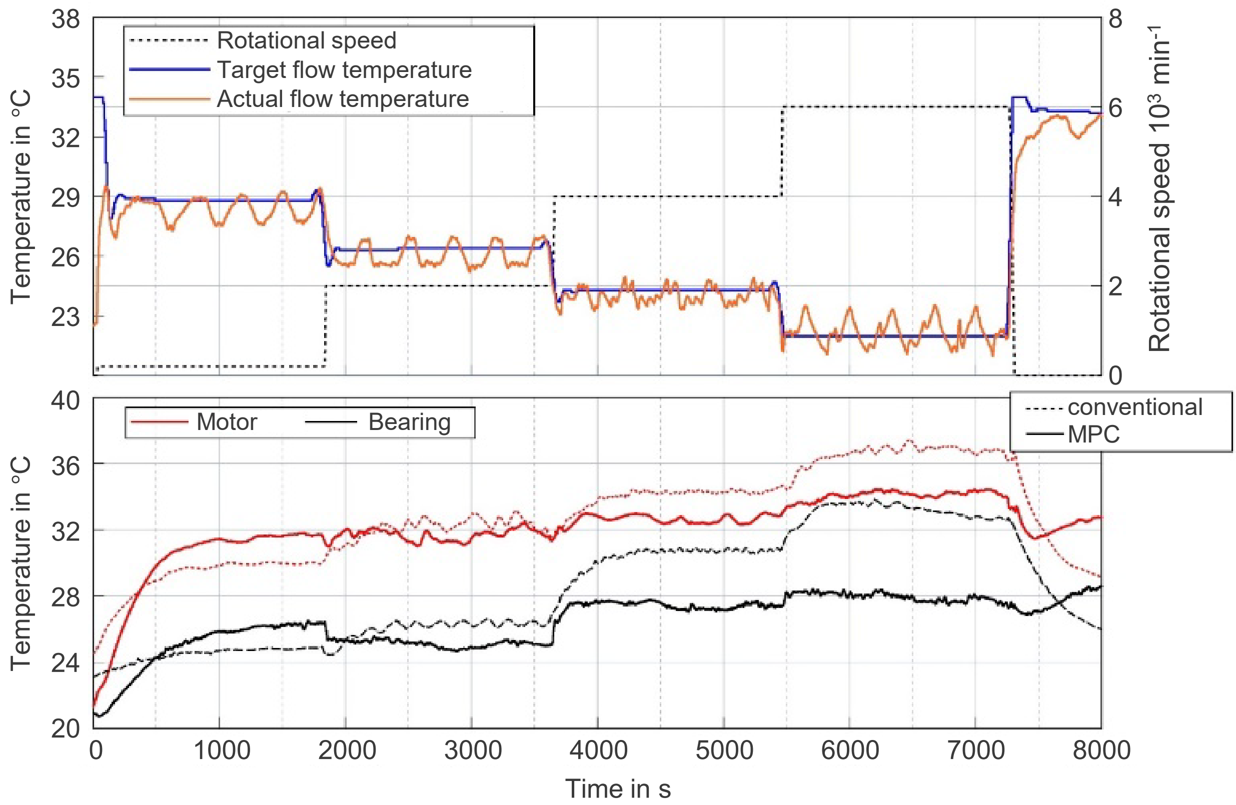

Figure 10: Example results on a motor spindle with MPC

Using the main spindle as an example, it was possible to demonstrate that the intelligent design of the active cooling system not only has theoretical potential, but can also be implemented in practice using the presented approach of MPC. In the next step, the transfer to the entire machine and the embedding of the power consumption in the control strategy will take place.

Furthermore, active cooling systems are merely a representative of energy-intensive auxiliary units. Also in the case of the use of cooling lubricant, it is conceivable to consider an overall evaluation of the influence of cooling lubricant (wear, process force/displacement, electrical power consumption) in the context of a MPC in order to optimize operation based on sustainable evaluation criteria.

4 Minimization of the process time

Another way to reduce the use of resources in production is to minimize process time. The following consideration shows that productivity-increasing measures in several dimensions can contribute to a more sustainable production.

1) Minimization of the base load share
   a. Maximizing productivity in machining changes the electrical power consumption per finished part. In our own investigations [16], it was shown that minimizing the process time goes hand in hand with minimizing the power consumption per finished part. Due to the high proportion of base load (cf. chapter 2), process time minimization with the associated base load savings clearly dominates the higher consumption of the electric drives as a result of the productivity increase.
2. Resource efficent machine tool
   a. The more productively a machine can be used, the fewer machines are required to produce the targeted quantity or number of workpieces.
3. Reduction of manufacturing costs
   a. By analogy with electrical power consumption, higher productivity ensures that fixed manufacturing costs are distributed over a larger number of components, for example for personnel and other operating resources.

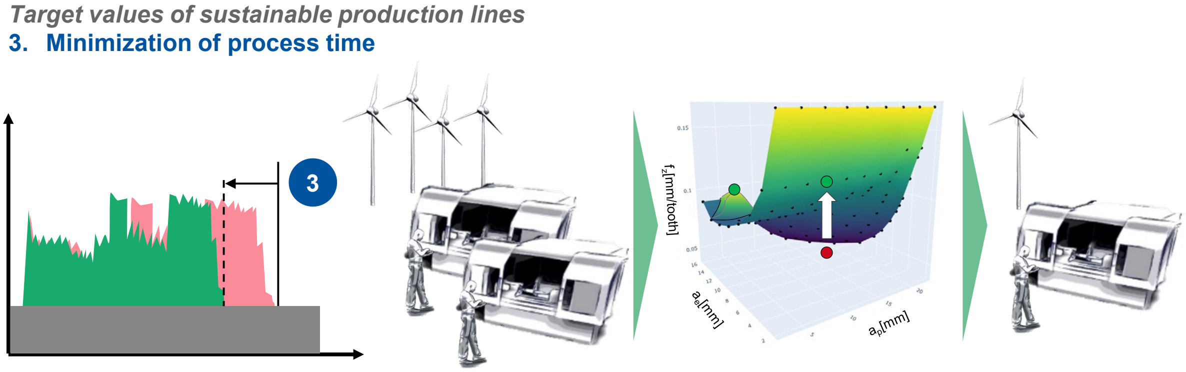

Figure 11: Minimization of process time as a target value of sustainable production lines

These three examples suggest that productive manufacturing processes with short process times should be aimed for. The metal removal rate Q can be used as a measure of productivity. This results from the product of the cutting width a_e, the cutting depth a_p, the rotational speed n and the feed per revolution f.

$$Q = \mathrm{a_e}\cdot\mathrm{a_p}\cdot n\cdot\mathrm{f}$$

In order to achieve the highest possible productivity, the individual influencing variables must be optimized so that the metal removal rate is maximized. Here, different limitations result from the static and dynamic receptance behavior and the power of the machine tool. [23]. In order for a minimization of the process time to actually lead to an increase in sustainability against the background of the three aspects listed above, it must be ensured that the positive effects outweigh possible negative effects. As in the case of optimized usage of auxiliary units (cf. chapter 3), a multidimensional optimization task arises whose solution can only be effectively achieved based on models or knowledge.

In the course of CAM planning, the individual process variables for the metal removal rate are defined in the NC program. Here, the process planner usually follows an individual set of rules based on his expert knowledge and on recommendations, e.g. from the tool manufacturer. During the ramp-up of a process, the selected process parameters are also checked and optimized by a machine operator with regard to their applicability. Experienced machine operators in particular are thus able to recognize unstable process areas acoustically and stabilize them by varying the rotational speed and feed rate.

The initial selection of process parameters can lead to processes that fulfill the required quality, but do not utilize the full technical potential of the machine and tool. Increasing data availability and rising computing capacities, in combination with expert and model knowledge, offer the possibility to open up hidden potentials and increasing productivity. To realize this in industrial applications, the solutions must not negatively impact the competitiveness of the respective company. Also, this means that manufacturing operations must not be disturbed. On the other hand, the investment must be as low as possible. In practice, therefore, there must be no changes in the machinery and no invasive changes on the individual machines. At the same time, only minimal adjustments should be made to the production process, e.g. feed rate or rotational speed changes, so that as few consequential changes as possible occur. Using model and expert knowledge, the history-based analysis of production data offers enormous potential to make all this possible and to optimize processes in such a way that their process time and, as a consequence, their resource consumption are reduced.

In this chapter, two concrete use cases are presented in which data- and knowledge-based process maps for ideal process parameters are generated. First, an approach for generating and using expert knowledge is presented. It's explained using the example of tool-specific cutting data. Subsequently, an industrially applicable, online-capable early warning system against process instabilities due to regenerative chatter vibrations is presented. The evaluation basis is represented by process-parallel recorded data.

4.1 Knowledge-based process optimization

The above examples illustrate that human experts strongly influence process planning and development. In the course of ramp-up in particular, an expert provides a comprehensive evaluation of the machining process based on his experiential knowledge. Through direct interaction with the machine, he can directly use sensory impressions, such as the perception of vibrations or the detection of burning chips, for locally differentiated evaluation of the manufacturing process. Experienced machine operators can then draw on their experience to initiate immediate optimization measures, such as adjusting the feed rate. These are not limited to process stability, but can also relate in particular to the productivity of the process or the component quality.

At present, the information relevant to the expert's decision-making process has not been considerably digitally recorded, which means that production engineering contexts cannot yet be mapped either systemically or by learning systems purely based on data. The key challenges therefore lie in the digitalization of expert knowledge, objectifying it and finally transferring it to unknown use cases in a context-sensitive manner. This enables manufacturing companies to preserve the heterogeneous experiential knowledge of their employees and make it available throughout the company. This is of crucial importance in the face of demographic change and the associated shortage of skilled workers.

Expert knowledge can be divided into three different levels of complexity:

- Explicit expert knowledge

This knowledge can be mapped on the basis of rules. The underlying relationships are either already recorded (e.g. formula, table book) or the expert has internalized them to the extent that he can justify them and, above all, formalize them independently (e.g. technology parameters for specific material-cutting material combination).

- Formalizable implicit expert knowledge

  This knowledge can only be mapped in a rule-based manner with the aid of data-driven algorithms. The expert needs in-depth information about the process and the current state of the production equipment in order to formalize his subjective assessment (e.g. "process is too noisy") within the framework of an objective rule (e.g. reduction of the feed rate when a critical acceleration value is exceeded).

- Non-formalizable implicit expert knowledge

  This knowledge cannot be formalized by a human expert. Although no objective or subjective indicators point to optimization possibilities of the process, the expert makes changes to the process (e.g. approach strategy A "better" than B).

In particular, the use of non-formalizable implicit expert knowledge poses a challenge. At the same time, this expert knowledge has the highest value for manufacturing companies, which is why it is imperative to capture it in order to increase productivity. The opportunity to capture expert knowledge presents itself whenever the expert intervenes in the process. In the context of ramp-up, this even happens iteratively, making this phase an ideal environment for digitizing human expert knowledge. In industrial practice, process evaluations and optimizations carried out by the machine operator are rarely reported back and taken into account without gaps. However, this feedback is essential for the mapping human knowledge. At the same time, the expert must be provided with meaningful data about the process directly at the machine in order to create comprehensive transparency and a resulting improved understanding of the process.

These two aspects motivate the approach shown in Figure 12 for knowledge-based process optimization. Modern machine tools have numerous sensors that are used for control. Classic examples are current and po-sition sensors. These data can be read out via the control system and used to generate a digital shadow [7]. The contextualization of the raw data is essential here, since the expert knowledge cannot otherwise be assigned to the production-related boundary con-ditions. At the same time, the raw data are also refined during the generation of the digital shadow (e.g. calculation of the tool displacement from the process forces) and enriched with additional characteristic values (e.g. tool wear condition). On the one hand, this sup-ports the transferability of the data and, on the other hand, makes it possible for the expert to visualize comprehensible characteristic values directly on the machine. By visualizing the raw and model data at the machine, the expert can be provided with data-based in-sights into the process, which are necessary to optimize productivity (cf. Figure 12 – Path 1).

In addition, an experienced machine operator can evaluate individual process sections. For this purpose, he has a programmable keyboard, with the help of which not only predefined labels but also textual optimization suggestions can be stored, which are saved together with the raw data. If this labeled data is now fed to an artificial intelligence (AI), it can learn correlation between the incoming data and the labels as part of a training phase. In future processes with sufficiently similar process situations, the system can provide a more inexperienced machine operator with recommended actions and instructions based on the expert knowledge learned in a context-sensitive manner (cf. Figure 12 – Path 2).

The user can accept or reject the suggestions made, thus enabling continuous learning. Human experiential knowledge for process optimization is thus gradually digitized.

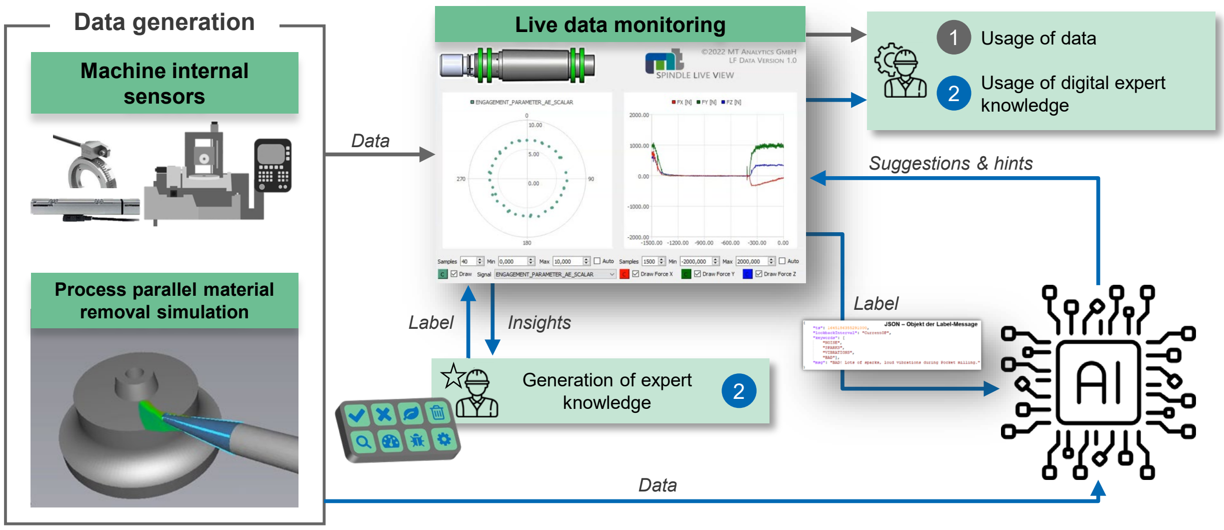

Figure 12: Data-driven learning from human expert knowledge

This concept can be concretized on the basis of a milling process. Multidimensional process parameter maps can be generated for the individual factors of the metal removal rate. These initially make it possible to represent the currently known optimum state of the process for a tool with regard to its parameters such as cutting width and depth as well as feed per tooth or cutting speed. An initial basis for this can be data from tool manufacturers or internal company standards. In the context of process planning, the data can be an orientation aid for the initial design of a manufacturing process. At the same time, the optimum values can also be used according to Figure 12 and compared with the current actual values parallel to the process. To determine the actual values, the cutting data, such as the feed per tooth, is determined on the basis of the machine's internal data and brought into a common context with regard to the cutting width and depth with the aid of a material removal sim-ulation. The machine operator thus receives immediate feedback as to whether the tool currently being used is being overloaded or whether increased productivity can even be achieved by, for example, a higher tooth feed (cf. Figure 13 – point 1). Direct optimization of the feed rate is then possible, for example via the feed rate potentiometer.

The machine operator can nevertheless deviate from the known optimum values during the running process. This is the case, for example, if he recognizes optimization potential in the use of tools or feels that the set values are inappropriately high. In these cases, process-parallel labels are assigned for tool use, on the basis of which the known opti-mum values are adjusted and the process parameter map is updated accordingly (cf. Figure 13 – point 2). In this way, the map selectively maps human expert knowledge and makes it available to other machine operators. By using the newly generated knowledge, manufacturing processes can be continuously optimized. The procedure can be transferred to other application areas, such as the context-specific evaluation of the spindle condition.

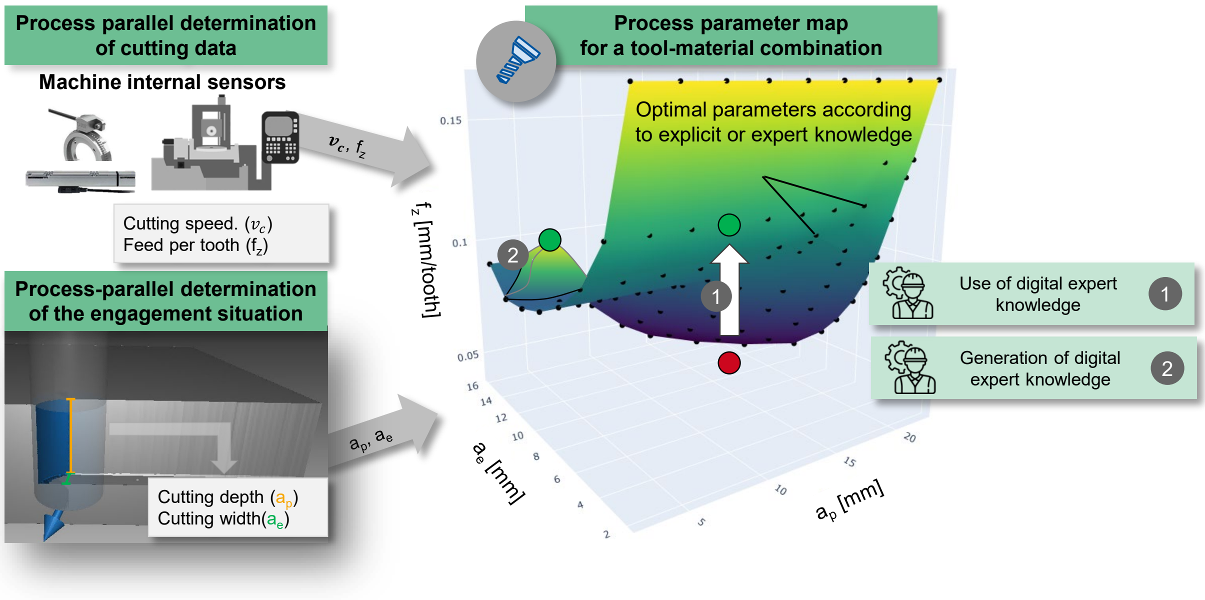

Figure 13: Process parameter maps for increasing productivity

4.2 Model-based process optimization

In addition to a knowledge-based approach, it is also possible to achieve sustainable process time optimization model based. As shown at the beginning of the chapter, the central conflict of goals between productivity and workpiece quality often leads to conservative process planning. In particular, the occurrence of self-excited and regeneratively self-amplifying vibrations (chatter) limits productivity. In order to exploit the full potential of a machine tool, a chatter prevention system is required that ensures high productivity while at the same time guaranteeing workpiece quality.

One approach to solving this problem is the targeted avoidance of process instabilities through a suitable choice of machining parameters for the process. So-called stability lobe diagramms, which show stability limits as a function of cutting depth and rotational speed, are an important tool for the optimum selection of process parameters. [24].

The efficiency of experimentally determined stability lobe diagramms has increased in recent years [25], but they are still too costly and uneconomical for use in small-batch production, since a new stability map must be determined experimentally in preliminary tests for each combination of tool, workpiece and machine. This is not compatible with the trend towards sustainable and resource-efficient production.

Alternatively, chatter vibrations and the associated stability limits can be determined model based. The simulative determination of stability limits is based on an analytical model that describes the interaction between machine and process. Numerous simulation approaches and methods exist [26]-[28]. However, up to now, no procedure exists which makes the model-based determination of stability limits usable in a process-parallel manner. This contribution presents a new concept for model-based online identification and early warning of process instabilities for a milling process.

The early warning system provides a tool to solve the existing conflict of goals between productivity and workpiece quality, especially in small batch and single part production.

The process-parallel checking of the stability limit particularly supports "first-part-right" approaches for the production of complex and expensive individual parts or small series in a resource-saving approach.

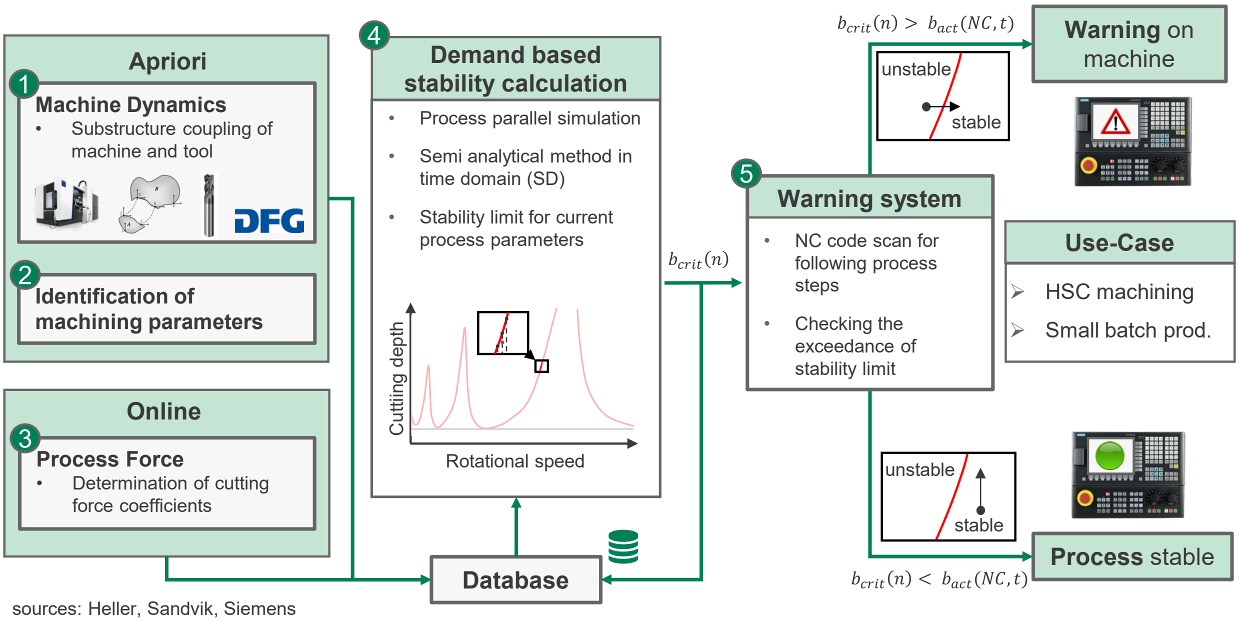

Figure 14: Methodology of the chatter early warning system

The methodology of the chatter early warning system is shown in Figure 14 and comprises five central blocks:

1. For model-based simulation, the central problem is an efficient representation of the variable dynamics of the machine-tool-material system. This is solved by new findings in the field of dynamic substructuring [29]. A one-time measured model of the machine tool is coupled with analytical tool models in order to reduce the experimental measurement efforts to a minimum.
2. With a material removal simulation based on a 3-D model of the blank and the NC code, the machining parameters can be identified a priori. The process variables required for the stability simulation, such as the cutting depth and width, can be extracted in relation to the different machining steps. The machining process is segmented on the basis of different tools and programmed process parameters. Based on this data, the most critical machining parameters can be identified for different segments of the process.
3. In addition to the machine dynamics, knowledge of the cutting force coefficients is required. Due to the major advance in the field of real-time acquisition of process forces, e.g. by spindle-integrated sensor technology [25], the cutting force coefficients can be parameterized parallel to the process. This is done on the basis of a comparison of measured and simulated process force with an ensemble Kalman filter, which has already been established for the application of a continuous parameter identification of analytical force models in the milling process [30]. By a process parallel identification of the cutting force coefficients, the input parameters required for the stability simulation can be determined based on the real boundary conditions of the running process. This offers an advantage over conventional model-based approaches, which simulate the stability boundary a priori and whose data basis relies on preliminary tests or tabulated values.

4. The stability limits are determined in parallel with the process within a demand-based simulation, which provides a statement on the machine control based on the current process parameters as to whether the running process is stable or unstable. Demand-oriented means that only the currently relevant speeds and cutting depths of the current machining step are evaluated for the stability simulation. Unlike conventional model-based approaches to stability simulation, therefore, the entire stability map is not calculated, but only a region around the currently relevant operating point. With this approach, the fast computing times required for the process-parallel approach can be guaranteed.
5. Based on the calculated stability limit, future machining steps can be checked in a kind of "look-ahead function" for exceeding the limit. The early warning system provides an online functionality that warns of potential process instabilities during a machining operation. Based on the warning, the occurrence of process instabilities can be prevented by operator intervention.

By using a database system, identified stability limits of specific pairings of machine tool, tool and material can be stored and used for downstream process optimization or future process designs.

5 Extension of use phase

Extending the service life of a machine and its individual components represents another approach to designing *sustainability in production lines* (cf. Figure 15). This first requires knowledge of the planned process, the associated and expected loads, and the wear behavior of the corresponding component. In the machine tool industry, there is currently a significant amount of data- and model-based knowledge that has been built up over many years. Simulated data can be used here to determine a more precise digital image of the wear condition. In this context, these simulated data can both supplement an ex-isting real data basis and form a previously non-existent data basis in order to predict condition development more precisely for different load collectives. On this basis, pro-cesses and the loads associated with the planned processes can be designed in advance in such a way that, for example, comparable productivity is achieved with a significantly extended service life of components such as ball screws or spindle bearings, thus con-tributing to increased sustainability in industrial production. Furthermore, a more reliable prediction of the technical service life provides plannable maintenance or refurbishing of systems and components entirely in the sense of the recycling economy.

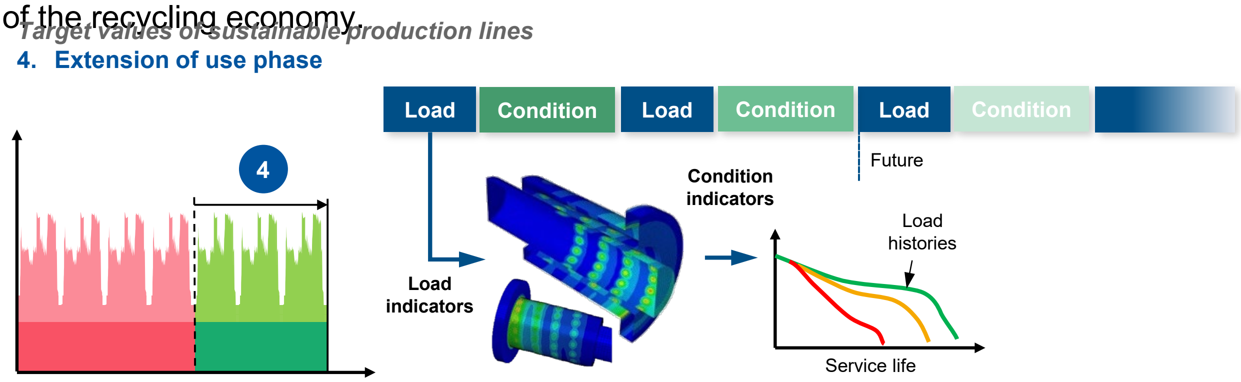

Figure 15: Extension of use phase as a target value of sustainable production lines

5.1 Identification of service life-reducing operating conditions

With regard to the machine tool, the main spindle represents an essential system component. In most cases, high-precision angular contact ball bearings are used to support the spindle shaft. These are subjected to high speeds and loads in the application, which make an all-embracing design of the component necessary. In addition to the theoretical service life and the maximum contact stresses, kinematic design parameters such as the spin-to-roll ratio or the circumferential ball advance are also considered. The latter describes a leading or trailing of the individual balls within the cage pockets in the direction of rotation. The reason for the formation of a certain ball advance lies in the type of bearing load. If, in addition to the axial preload, radial forces or moment loads occur due to the process loads, a contact angle change occurs at the inner and outer contact along the bearing circumference [31]. This results in the modulation of an orbital velocity about the bearing axis, which ultimately leads to the said ball forward and backward motion. If the geometrically possible free space of movement of the balls is exceeded, significant contact forces between the cage and the balls can occur and lead to bearing failure due to increased friction and wear. Accordingly, this value, together with the maximum contact stress and the spin-to-roll ratio, represents a central design parameter of spindle bearings [23].

Since the ball motion is influenced by the load-dependent friction state in the rolling contacts, an exact description with kinematic formulas is very difficult. As a result, deviations between the calculated and the actual ball kinematics occur when the influence of process-like loads is considered with common calculation approaches [32]. This leads to the motivation to measure the ball motion in operation under static and dynamic loads in order to optimize existing calculation approaches and thus make them more reliable, and to identify unfavorable load conditions for the bearing kinematics during machining in order to extend the service life of spindle bearings. Current research work at the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University is dedicated to this project, in the context of which a spindle bearing test rig (Figure 16) was developed, which makes it possible to generate defined static and dynamic bearing loads, to determine these by means of the resulting shaft displacement and to measure the ball motion that occurs.

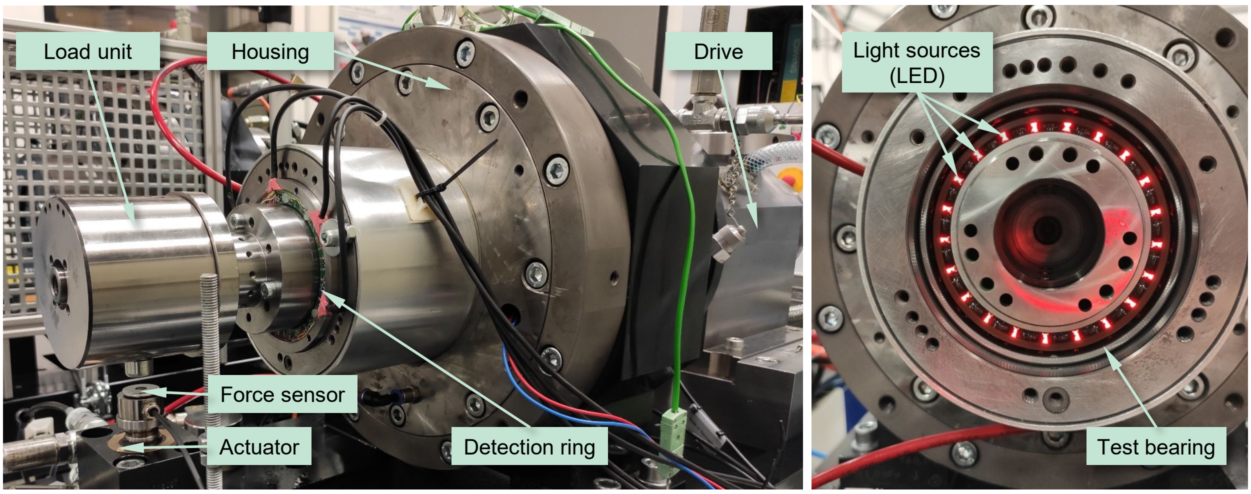

Figure 16: High-speed bearing test rig for measuring ball motion

For this purpose, as shown in Figure 17 an optical measuring system for detecting the ball position was first developed. The system uses light sources that shine through the spindle bearing between the inner ring and the cage. Opposing photodetectors capture the light signal, which is intermittently shadowed by the balls. To determine the movement of each individual ball, several of these photoelectric sensors are distributed around the circumference of the bearing. After evaluation of the sensor data, a sampling rate of 40 MHz enables a resolution for ball detection at the sensor positions of less than 2 µm. [32]

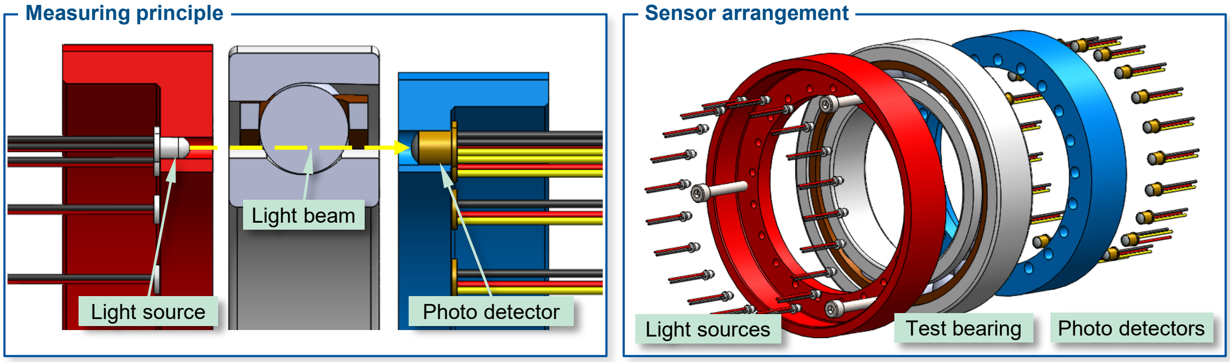

Figure 17: Optical measuring system for detecting the ball position in a spindle bearing

In addition, the shaft displacement in front of the test bearing is recorded synchronously by means of three eddy current sensors arranged radially and axially. From this, the acting loads can be determined both in magnitude and direction in real time. For load application, two preloaded piezoelectric actuators, which are positioned at 90° to each other, are used to generate the dynamic radial forces. The forces are applied to the shaft via a load unit, which decouples the rotation of the spindle shaft with another bearing assembly. The design of the load unit allows both tensile and compressive forces with high amplitudes of up to 1,000 N to be applied without clearance. This allows the test bearing to be loaded with stationary dynamic forces and varying frequencies. In addition, the influence of rotating loads as well as an unbalance, which corresponds to a force rotating with the shaft rotational frequency, is investigated [32]. Thus, the influence of typical load conditions on the circumferential ball advance can be recorded and evaluated. The successful prototypical implementation of the measuring systems for detecting the shaft displacement and the ball positions in a milling spindle now makes it possible to identify service life-reducing operating states during machining on the basis of real dynamic process loads.

In order to make the developed measurement system usable for industrial production in the next step and to contribute to sustainability, the necessary data basis for generating a detailed and reliable load map for this machine component must first be generated (see Figure 18). Based on this information and the process-parallel recording of transferable load conditions, optimal operating conditions for the main spindle bearings can then be observed or critical conditions avoided in order to extend the actual service life of this relevant machine component. In combination with machine learning approaches, learning models can also be developed on the basis of the historical data, which can make a reliable prediction of the remaining technical availability of the individual component.

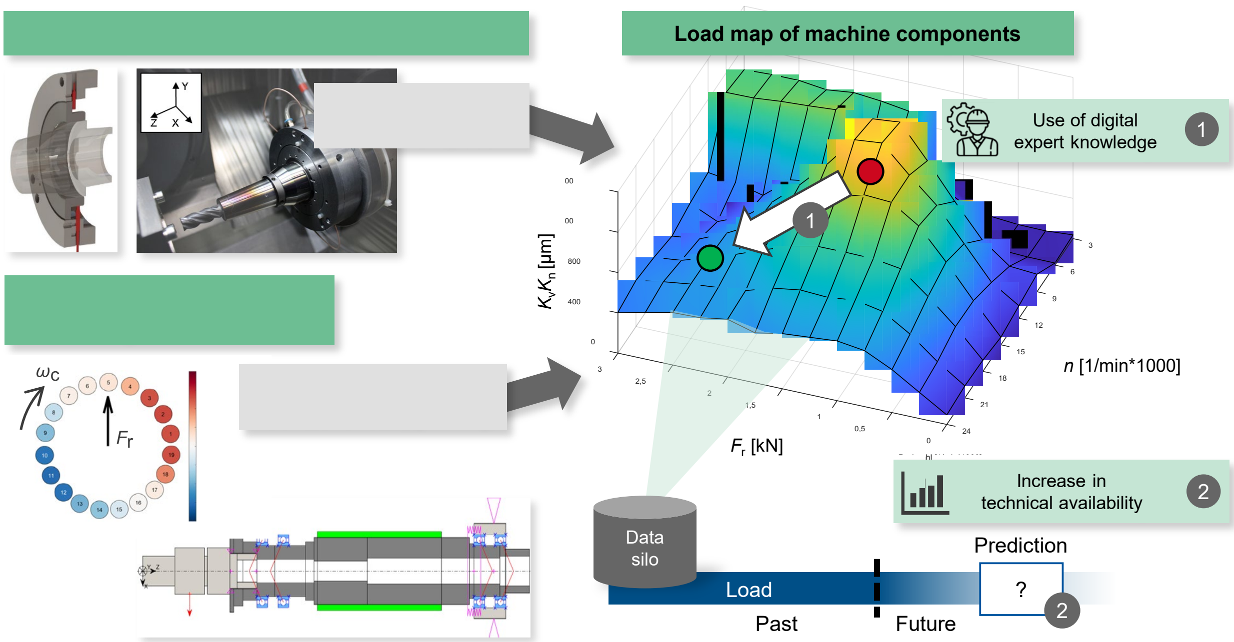

Figure 18: Load map of a spindle bearing for extension of service life

5.2 Extended service life calculation of ball screws

Another application example for the extension of the service life of machine components in the context of current research work at the WZL is the extension of current service life calculations of ball screws on the basis of continuously parameterizing models. A ball screw is used in particular in feed drives of machine tools, where it is used to convert a rotary motion into a linear motion. Compared to other feed drive systems, the component offers a number of advantages, such as high efficiency due to rolling friction, high precision and sufficiently high stiffness [32].

As part of the feed axis, the ball screw is responsible for precise positioning and thus plays a central role in the machine tool. The resulting load and the associated service life depend on the productivity of the overall machine due to the position of the component in the force flux. In terms of resource-saving production, the best possible utilization and the extension of the service life of this component are therefore obvious.

Ball screws exhibit clearly variable internal load distributions depending on their geometry and the prevailing load. Although finite element models allow the determination of these distributions, they are insufficiently taken into account, especially in the service life calculation. In the following, a method for the consideration of discrete location load distributions in the service life calculation of ball screws is presented.

When calculating the service life of ball screws, an equivalent load and speed is generally calculated, which combines various load situations as well as any preload that may be present. The service life resulting from the assumed load spectrum L in revolutions is then calculated by the quotient of the load F_m and the load capacity, which is expressed in the form of the basic dynamic load rating C_a [33]:

$$L = \left(\frac{C_a}{F_m}\right)^3 \cdot 10^6$$

However, it should be noted that the service life calculation according to DIN ISO 3408-5 does not take into account some influences such as the motion profile or existing assembly deviations due to the underlying simplified service life model. According to the manufacturers, ball screws should only be loaded in the axial direction. Current calculation methods assume that moments or radial loads are absorbed by rigid linear guides assembled parallel to the ball screw. Multi-axial loads are thus not taken into account when calculating the remaining service life. In the case of machine tools, however, assembling deviations between linear guides and ball screws can lead to additional loads. Due to the high rigidity of the guideway system, even small deviations can lead to high constraining forces, resulting in a considerable variation in the internal load distribution. In addition, depending on the motion profile, different areas of the spindle are subjected to different levels of stress, resulting in uneven use of the wear reserve along the length of the spindle. [34]

For these reasons, the existing service life theory was extended at the WZL to include the calculation of a spatially resolved fatigue service life. Based on a life model reduced to the ball contact, spatially discrete component loads and the associated cumulative load changes are calculated. To determine the occurring contact stresses, the simulation program "MTPlus" developed at the WZL (cf. [35]) is used. The calculation of the fatigue life, which is dependent on the driving cycle, requires the accumulation of the location-related load cycles, taking into account the acting ball load. For this purpose, the raceways of the spindle and nut are divided into segments at ball spacing and the driving profile is examined for the frequency and intensity of the load changes [34]. This results in the load profile shown in Figure 19, which shows the transfer of a motion and load profile from a time series to a matrix notation, significantly reducing access time and data volume. The load on each contact point is determined from look-up tables calculated in previous simulations, depending on the load direction and magnitude [34].

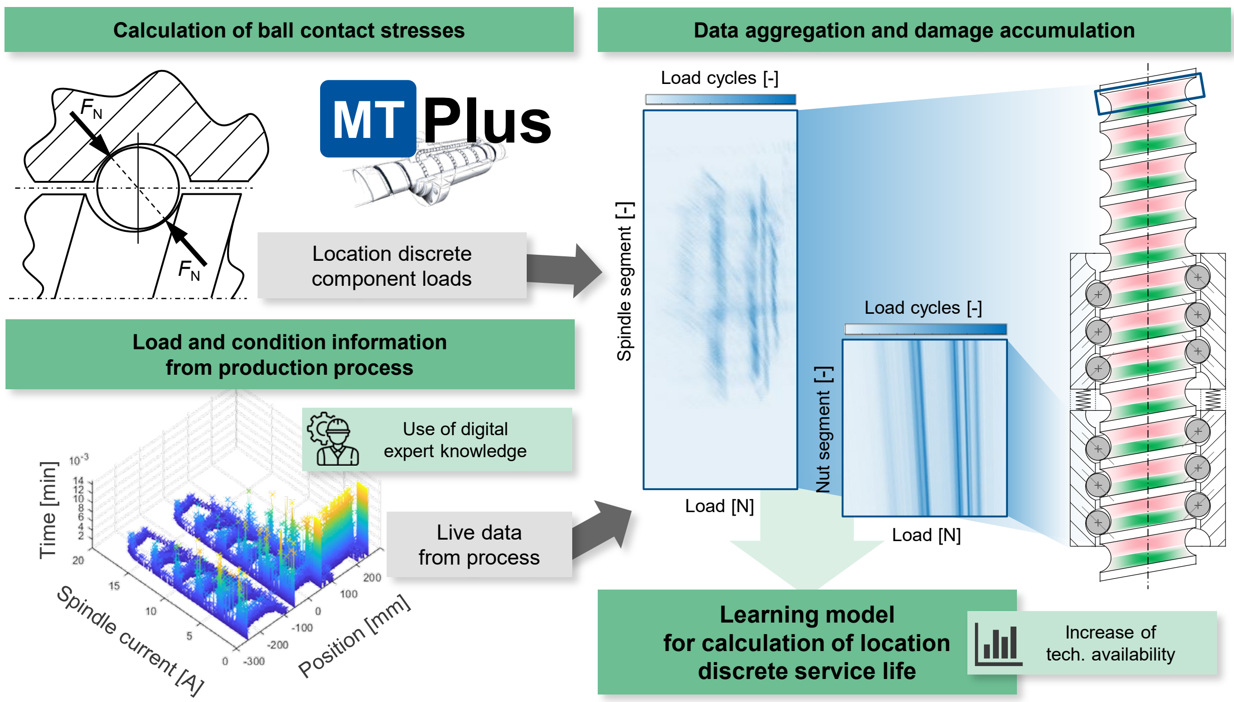

Figure 19: *Hybrid model for the extended service life calculation of a ball screw according to [34]*

The prediction of the resulting total service life is subsequently obtained by analyzing the determined segment service lives by applying Miner's linear damage accumulation, which takes into account the total damage of each raceway segment [34].
Combining the fatigue model with live information on the actual load collectives occurring in production increases its predictive quality. This further increases the reliability of the maintenance planning for the component and can thus contribute to increasing sustainability.
For this purpose, the extended life model, as described in [15] was adapted by means of feedback from load and condition information from the production process, such as spindle drive current or displacements. The result is a learning model that can perspectively be used in terms of data sharing in the context of the machine tool, as already described in chapter 5.1, beyond the boundaries of the company. On the basis of this approach, components can be designed more efficiently and thus demonstrably better utilized, which saves resources in industrial production.

5.3 Enabling optimized recycling economy

The two use cases described allow a precise prediction of the technical service life of the components, taking into account different load collectives. On the one hand, this can be used to design processes and associated loads in such a way that comparable productivity is achieved with a significantly extended service life. On the other hand, it also enables optimized recycling economy, since the end of the service life and thus component replacement or refurbishing can be planned more easily. In the context of machine tools, reliable condition-based prediction of remaining service life plays an important role in extending service life, especially for high-priced and essential subsystems such as the main spindle. With reference to the first use case presented, the load condition of the spindle bearings can be determined more accurately, less damage or failure occurs, and the main spindle can find its way into another usage cycle after a due reconditioning. A targeted reconditioning or renewal of such systems subject to wear and tear extends the life cycle of a machine and thus contributes directly to minimizing the holistic use of resources.

In addition to condition-based maintenance and reuse of high-priced components, a modular design of the machine on the hardware and software side represents a complementary approach to optimizing the recycling management. For example, if a modular design, which also takes into account the replacement of individual components, is already provided for during the design process of a machine and its subsystems, this enables fast and flexible installation and removal of machine components during maintenance. The result is an immediate reduction in downtime. If the machine also has an update capability, its life cycle can be additionally extended, for example by replacing an outdated software module from the control system.

6 Vision of data sharing

In addition to manufacturing optimization, the digitalization of expert knowledge enables companies to exchange knowledge between experienced on inexperienced personnel. The extraction of knowledge and its persistence is initially protected corporate know-how that offers cross-departmental utilization opportunities. Furthermore, the storage of expert knowledge helps companies to counter demographic change, as this knowledge is now permanently available.

However, the overriding goal must be to make data and know-how available across companies. Only in this way is it possible to increase sustainability on a broad scale in the sense of the FESG factors. In order to create global competition between companies to share sustainability-enhancing data or sustainability-enhancing know-how on a broad scale, monetary incentives must be created through new frameworks in the form of new business models. The prerequisite for this is always data security and anonymity. The stored process parameter values do not allow any conclusions to be drawn about the manufactured product or its production strategy. Through the targeted sale of these process parameters, processes can be optimized across companies without jeopardizing their own competitiveness. The pricing of this data must be data-based on the basis of the individual increase in efficiency. Cross-company knowledge trading not only increases the sustainability of manufacturing companies, but also opens up a new market for data and knowledge trading.

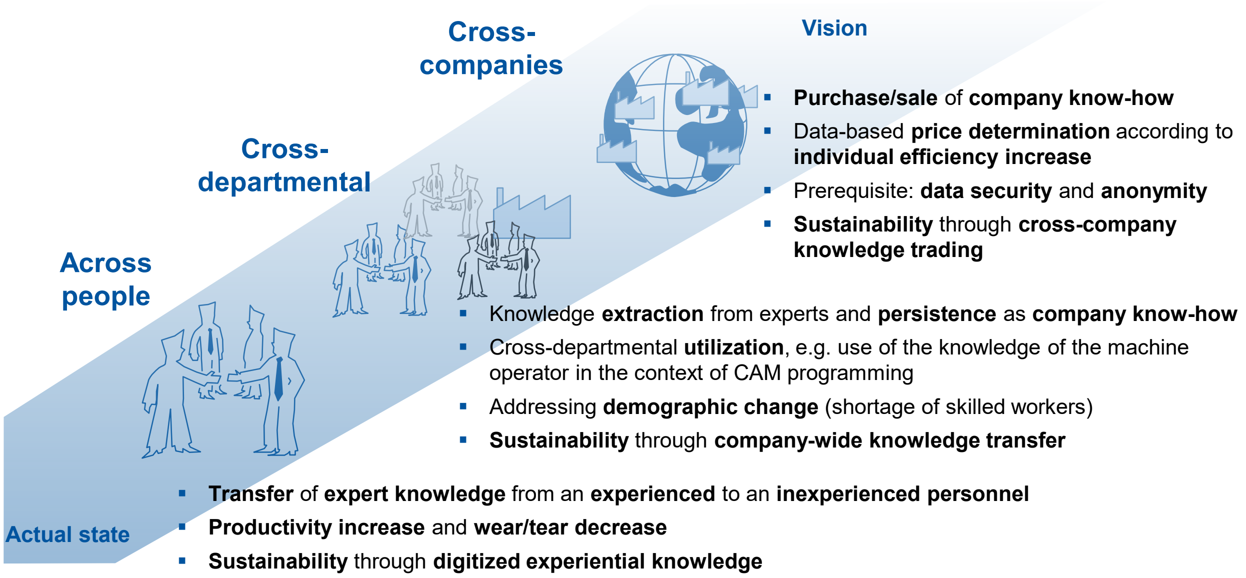

Figure 20: Data sharing as a contribution to increase sustainability

7 Summary and outlook

Due to profound global change processes, the production industry is confronted more than ever with the transformation of sustainability. In this context, the article is dedicated to the goal of providing concrete approaches for increasing sustainability by minimizing the overall use of resources in industrial production. In the context of the use case of a machine tool, the following four target values for designing *sustainability in production lines are* named: Reduction of the process-independent base load of auxiliary units, demand-oriented operation of energy-efficient auxiliary units, minimization of process time, and maximization of use phase.

Based on the latest research activities of the WZL, concrete application cases are presented for the individual target values. While the use of energy-efficient auxiliary units is discussed for achieving a base load reduction, the chapter on the demand-oriented use of these energy-efficient auxiliary units deals specifically with an intelligent model-predictive control for active cooling systems of machine tools. Model-predictive cooling makes it possible to shorten long warm-up phases of a machine and thus to manufacture immediately in line with quality requirements while at the same time reducing energy consumption. Energy consumption per component can also be reduced by minimizing process times through productivity-enhancing measures. For this purpose, expert knowledge regarding optimal operating parameters, e.g. from process planners or machine operators, must be digitized and objectified and finally be available in transferable form through characteristic values. The comprehensive availability of expert knowledge is then the basis for increasing productivity and quality. This paper presents an approach for using and generating digital expert knowledge using the example of process parameter maps.

Analogously, this procedure can be applied to extend the service life of machines and relevant components such as the main spindle. Along the service life, load states are recorded parallel to the process. The transferability of the parameters enables the use of machine learning approaches to predict the condition and service life as a function of the operating parameters. The expert knowledge generated, e.g. in the form of information on optimum operating conditions for a main spindle, must subsequently be digitized in turn. In this move, the circular economy is also optimized, since component states are known more precisely, less damage or failure occurs, and the components can thus find their way into a further utilization cycle. With regard to the extension of the service life, the focus of the article is on the presentation of a measuring system for the process-parallel determination of service life-reducing operating states of the main spindle bearing.

The use cases for increasing productivity and useful life are based on the extraction and digitization of expert knowledge. Finally, a vision is presented for the use of this knowledge within the company and across-. The extraction and digitization of expert knowledge supports companies in the long-term preservation of in-house know-how. The transfer of expert knowledge to new, inexperienced personnel is facilitated and the shortage of skilled workers resulting from demographic change is counteracted. Furthermore, cross-departmental utilization opportunities are offered, for example by using the knowledge of the machine operator in the context of CAM programming. In order to create global competition between companies to share sustainability-enhancing know-how on a broad scale, monetary incentives must be created through new frameworks in the form of new business models. The -focus here is on data-based pricing in accordance with the individual sustainability enhancement achieved, as well as observance of data security and data anonymity.

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3.2 Sustainable Production-as-a-Service

C. Brecher, O. Petrovic, Y. Dassen, P. Blanke, M. Trinh, S. Wurm

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Abstract

Sustainable Production-as-a-Service
Production contributes significantly to global CO_2 emissions. Increasing efficiency, conserving resources and avoiding overproduction are economic goals that are increasingly coming into focus in the context of sustainability. The use of digital technologies can address these goals and enable the exploitation of previously underutilized sustainability potentials. Digitization is an overarching solution module that enables data to be collected and evaluated, and based on which optimized production processes can be developed. Holistic data collection across the entire lifecycle of a product is achieved, for example, with the help of digital twins. Building on this, virtualization offers the potential to significantly extend the life cycle of production systems. Other promising technologies are virtual environments such as the Metaverse or artificial intelligence. The often high investment requirements or the lack of transparency about the return on investment and the lack of the necessary expertise regarding the implementation and maintenance of digital technologies inhibit many small and medium sized enterprises in their implementation. This circumstance can be countered with the encapsulated offering of digital solutions "as-a-Service" (aaS). This article therefore explains the opportunities for increasing sustainability through digital technologies and the prerequisites for their implementation. Practical examples will then be used to illustrate the possibilities for using these technologies within the framework of "as-a-service" models.

Keywords: digitization, control virtualization, Metaverse, AI, as-a-service

Kurzfassung

Nachhaltige Produktion-as-a-Service
Die Produktion trägt signifikant zu den weltweiten CO_2-Emissionen bei. Effizienzsteigerungen, Ressourcenschonung und Vermeidung von Überproduktion sind wirtschaftliche Ziele, die nun auch im Kontext der Nachhaltigkeit verstärkt in den Fokus rücken. Der Einsatz digitaler Technologien kann diese Ziele adressieren und die Ausschöpfung von bisher wenig genutzten Nachhaltigkeitspotenzialen ermöglichen. Die Digitalisierung ist ein übergreifender Lösungsbaustein, der das Erheben und Auswerten von Daten ermöglicht und auf dessen Grundlage optimierte Produktionsabläufe entwickelt werden können. Eine ganzheitliche Datenerfassung über den vollständigen Lebenszyklus eines Produktes hinweg erfolgt beispielsweise mit Hilfe von digitalen Zwillingen. Darauf aufbauend bietet die Virtualisierung das Potenzial, den Lebenszyklus von Produktionssystemen signifikant zu verlängern. Weitere erfolgsversprechende Technologien sind virtuelle Umgebungen wie das Metaverse oder die künstliche Intelligenz. Der zum Teil hohe Investitionsbedarf bzw. die mangelnde Transparenz bezüglich des Return of Investment und das Fehlen der notwendigen Expertise hinsichtlich der Implementierung und Pflege der digitalen Technologien hemmt viele Mittelständler bei der Umsetzung. Diesem Umstand kann mit dem gekapselten Anbieten der digitalen Lösungen „as-a-Service“ (aaS) begegnet werden. Daher werden in diesem Beitrag die Chancen zur Steigerung der Nachhaltigkeit durch digitale Technologien sowie die Voraussetzungen für deren Umsetzung erläutert. Anschließend werden anhand praktischer Beispiele die Möglichkeiten der Nutzung dieser Technologien im Rahmen von "as-a-Service"-Modellen aufgezeigt.

Schlagwörter: Digitalisierung, Steuerungsvirtualisierung, Metaverse, KI, as-a-Service

1 Introduction

In 2015, the environmental, economic and social goals of the United Nations were specified by the adoption of the 2030 Agenda with the definition of 17 goals (Sustainable Development Goals, SDGs) [1]. The term "sustainability" thus encompasses several aspects and goes beyond the widespread understanding of climate and environmental protection through resource conservation and emissions reduction. The 12th goal of the SDGs specifically addresses more sustainable consumption as well as the more sustainable production of goods and thus calls on companies to take direct action with regard to their products and processes. Accordingly, this goal is pursued by most manufacturing companies through their strategies to promote sustainability [2].

Production causes 42% of global CO2 emissions (from fuel combustion) and thus accounts for a significant share. In combination with logistics, it even accounts for 53%. In order to limit the global temperature increase to 1.5°C, a significant reduction of emissions in production is therefore required (see *Figure 1*). The aim must be to reduce resource consumption and avoid overproduction, while at the same time focusing on the efficiency and longevity of production lines and the reuse of components in the sense of a circular economy.

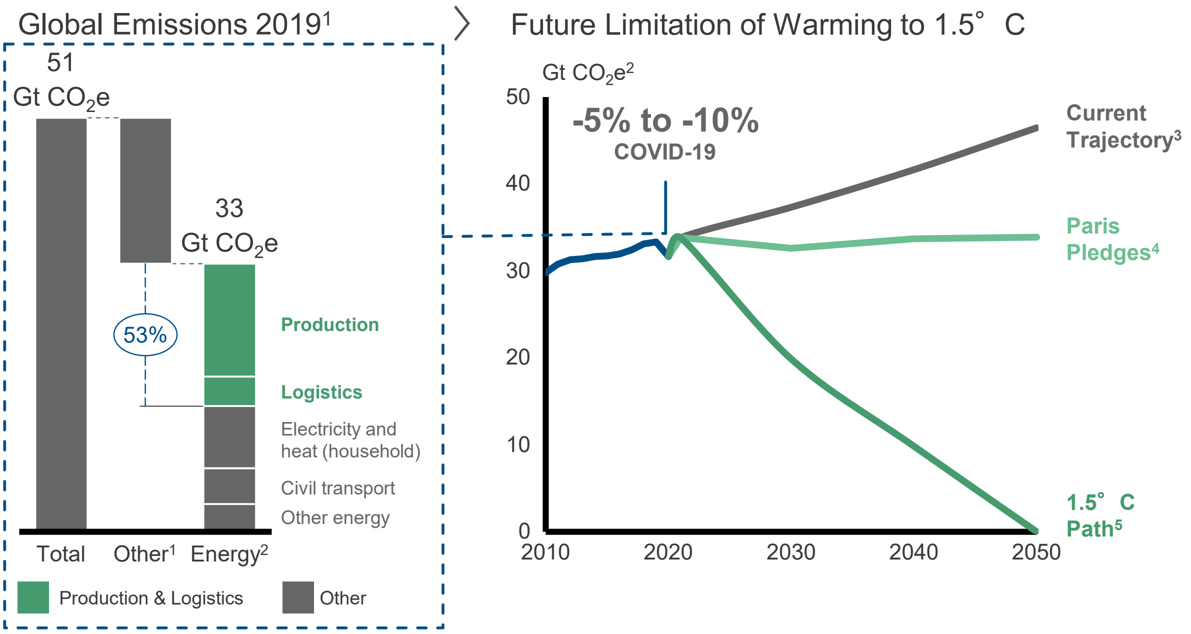

Figure 1: Reduction of emissions in production necessary. Sources: IPCC; IEA; Climatewatch; BCG[1]

The use of digital technologies can address these goals and offers the opportunity to exploit previously underutilized potential with regard to sustainable and circular production. Digitization is an overarching solution module that enables the collection and evalu-

[1] 1. Non-energy-related emissions from agriculture, waste, industrial processes and products 2. CO2e emissions from fuel combustion only 3. Assumes that energy-related emissions continue to grow at 1.1% per annum after 2018 4. Assumes that countries decarbonize in accordance with their intended nationally determined contributions (INDCs) by 2030 and then continue on the same emissions trajectory until 2050 5. Assumes 45% reduction by 2030 and net zero by 2050.

ation of data, for example, on the energy consumption of individual processes or machines, and thus enables the identification of critical processes. Building on this, the virtualization of functionalities, the use of the industrial Metaverse and of artificial intelligence (AI) in production, among other things, offers promising opportunities for increasing sustainability.

However, the sometimes high investment requirements and the lack of transparency with regard to the return on investment (ROI) and the lack of the necessary expertise regarding the implementation and maintenance of these digital technologies are currently still hampering many SMEs in their implementation. At the same time, fluctuating customer demand, unstable supply chains and the associated production downtimes require a certain degree of flexibility and agility, which are countered by long-term investments.

This can be addressed by offering encapsulated digital solutions "as-a-Service" (aaS): On the economic side, the associated payment models offer companies entry opportunities with significantly reduced financial risk, while the demand-driven utilization of resources promoted by aaS supports sustainability. The customer is given the opportunity to try out a wide range of digital technologies, physical assets and associated services to find an optimal solution.

This article therefore explains the opportunities for increasing sustainability through digital technologies and the prerequisites for their implementation. Practical examples are used to illustrate the possibilities of applying these technologies in the context of aaS approaches.

2 Sustainability in Production

2.1 Sustainability Balance in Production

The environmental impact is influenced by diverse factors, with about half of the ecological footprint being attributable to CO_2 emissions. In terms of sustainability, reducing the ecological footprint is one of the primary goals of manufacturing companies [3].

Many strategic decisions, such as reducing the use of resources, show an overlap between the goals of sustainability and economic efficiency. In the meantime, however, decisions are no longer made on the basis of purely economic evaluation criteria, but ecological factors are increasingly being incorporated into the decision-making process. An ecological balance sheet not only provides information for business partners and customers, but also insights into critical processes that have a negative impact on sustainable manufacturing of a product. [4], [5].

In order to evaluate the sustainability of products, realistic, meaningful and comparable values are necessary, which is why manufacturing companies have developed accounting approaches for quantification. The setting of suitable balance limits is a great challenge, since not every influence can be directly measured and assigned to a specific product. A considerable part of the energy consumption and emissions is caused by auxiliary processes, infrastructure, transport or peripherals such as lighting, heating or air conditioning and must therefore be included in the overall assessment.

Life Cycle Assessment (LCA) provides a comprehensive metric for accounting for products throughout their life cycle. In an LCA analysis, the entire life cycle of a product or service can be accounted for, from manufacturing to end of life (EOL). An LCA analysis goes beyond greenhouse gas (GHG) accounting and considers other factors that have an impact on the environment, such as groundwater pollution. Quantification always refers to the status of the product in its life cycle. For example, it can be balanced from production to leaving the factory (cradle-to-gate) or from production to EOL (cradle-to-grave) [6].

ISO 14060 is a widely used guideline for the preparation of financial statements. [7]. The series of standards provides a framework for quantifying, monitoring, reporting, and validating or verifying greenhouse gas emissions [8]. CO_2 equivalents are introduced to simplify comparability. The emissions of the individual greenhouse gases (CO_2, CH_4, N_2O, etc.) are calculated separately and then converted into CO_2 equivalents on the basis of their potential for global warming [7]–[9]. The standard can be seen as a generic standard for quantifying the CO_2 footprint of products (PCF - product CO_2 footprint) [8]. In addition to the PCF, accounting can be carried out on the company side and quantified in a Coperate Carbon Footprint (CCF - corporate CO_2 footprint) [10].

2.2 How to make production more sustainable?

Various solution concepts exist for implementing a more sustainable production. In this paragraph, approaches of the circular economy, the increase of efficiency and the extension of the service life of products are explained in more detail (see *Figure 2*).

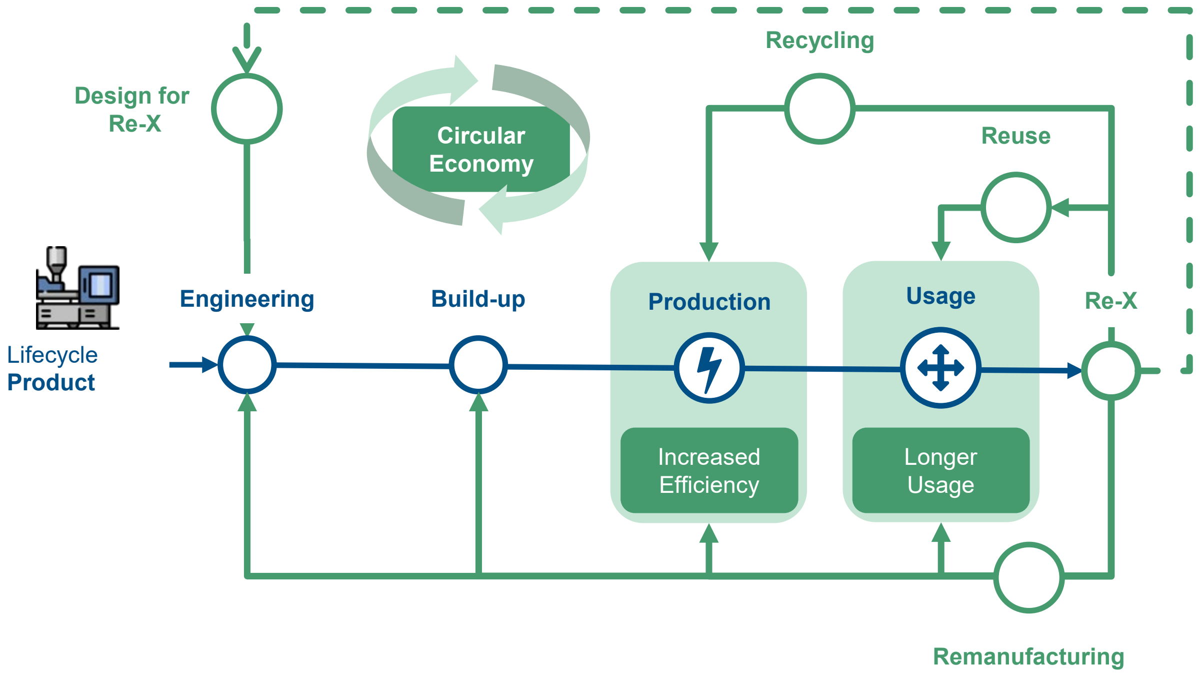

Figure 2: Sustainability potential along the value chain

Circular Economy

The status quo of production today is typically based on linear processes of "take, make and dispose", resulting in high consumption and low reuse of raw materials. When considering the entire life cycle of a product, the circular economy can make a promising contribution to the conservation of resources. Viewed globally and across all sectors, 70% of the materials already available can be used to meet the needs of humankind. For this reason, the Japanese government, for example, has decided to establish a complete closed-loop system by 2050 and is promoting corresponding measures [11].

Various approaches can be taken to implement a circular economy. So-called "R-strategies" have become established in the literature, which identify fields of action (e.g. recycling, remanufacturing or reuse) in order to minimize the consumption of materials and resources. All lists of R-strategies are similar to each other and differ mainly in the number of economic strategies they propose and relate to circularity. In the production environment, the following examples of R-strategies are common (see *Table 1*) [12], [13].

Table 1: Selection of R-strategies of circular economy.

Reuse
Reuse of products: Reuse of a discarded product that is still in good condition and fulfills its original function by another user
Remanufacture
Remanufacturing: parts of a discarded product are used in a new product with the same function
Recycle
Recycling: Materials that have already been processed are reprocessed to achieve the same or lower quality
Reduce
Reduction: The resources required are kept as low as possible. The greatest influence can be exerted in the product design process, e.g. by minimizing the initial material requirements with the aid of topology optimization

Such R-strategies can be supplemented by further points. In the literature, everything related to the pursuit of material and resource conservation is often assigned to the circular economy. Increasing efficiency, for example, can be assigned to the Reduce strategy, or extending the service life to the Rethink strategy. [12], [13]. In the following paragraphs, increasing efficiency and extending service life are not thematically assigned to the circular economy, but are treated as independent measures.

In terms of production, the feasibility of a circular economy depends on the following main factors: Increasing information availability, Design for Re-X and implementing digital solutions along the value chain. One information provider, digital solution and thus enabler for the circular economy is the Digital Twin, which is described in more detail in this context in chapter 3.1 [14], [15]. From a technical point of view, Design for Re-X is a fundamental building block for establishing closed-loop capability as early as the product design stage. The goal of the product design process is to achieve the best possible performance of the product while minimizing negative impacts on the environment throughout the product life cycle. This implies design fundamentals such as durability, modularization or standardization, ease of maintenance and repair, upgradeability, and opportunities for full disassembly and reassembly, e.g., to enable a second use of the product through updates or retrofits [14].

Extension of Service Life

A longer service life of a product can be achieved by increasing its lifetime or by using it more intensively during that time. Extending the service life can help to spread the emissions caused by the product over a longer period of time. However, this may conflict with product improvements during the use phase, which may result in a lower environmental impact during use. It is important to consider that the reduction in emissions from an optimized new product must be proportionate to the environmental impact of a new purchase. Designing a product for a certain level of performance may be worthwhile to ensure the best possible utilization. While more intensive utilization may result in a shortened service life, it may also mean earlier procurement of an improved product. Intensive utilization of aircrafts during their service life or sharing of vehicles are examples of optimized strategies with regard to service life. [16]. Crucial to such an approach is the availability of detailed information on the manufactured products, which must already be recorded during product development and production. Only with the help of a solid data basis can an emissions-optimized service life be determined.

There are various approaches to extending the service life of a product. On the one hand, the product can be designed to be more robust. In this case, the optimal compromise must be found between higher emissions during production and savings through longer or more intensive use. Alternatively, with the help of modularization and standardization, a repair or retrofit can contribute to an extension of the service life. [16], [17]. Predictive maintenance allows optimal maintenance intervals to be predicted and the service life of a tool, for instance, to be extended [18]. Moving hardware components such as machine controllers to virtuality can also lead to a longer service life due to better updateability, as described in chapter 3.2.

Increase of Efficiency

Increasing efficiency through lean production and efficient processes is not only a goal of manufacturing companies from an economic point of view, but also contributes to increasing sustainability [19]. The efficiency of a production system has a direct impact on the emissions emitted during manufacturing of products. Reducing energy consumption, saving production steps, designing the machine tool to meet customer demands, or avoiding scrap during the start-up phase or production ultimately leads to a reduction in PCF. The emissions saved in this way improve the balance during the manufacturing phase of the product life cycle. Digital technologies, such as the use of data, virtualization, the use of the industrial Metaverse or AI, which are presented in chapter 3, can also lead to great efficiency potentials.

3 Enabler for a sustainable Production

The previous chapter described how sustainability can be defined from the perspective of production technology and what approaches exist for its implementation. Individual stations in the life cycle of production systems can be optimized or even new ones created in order to avoid rejects, expand functions and thus extend the life cycle or transfer it into a circular one. In the following, four promising digital technologies are presented and their possible influence on sustainability is outlined.

3.1 Digital Twin

Digitization and sustainability are not contradictory; on the contrary, it is only through digital solutions that sustainability goals can be implemented. Collected data along the value chain and the product life cycle offers previously untapped potential with regard to sustainable and circular production. The levers for sustainable production are equivalent to the core objectives of digitization in the context of Industry 4.0, such as improving productivity (e.g., rapid reconfiguration of systems) and the efficient use of resources (e.g., avoiding rejects). [20]. Digitization is thus an overarching solution component for companies to develop measures to reduce their environmental impact. Digital technologies essentially fulfill two core tasks: Capture and enable. With the help of the Digital Twin, for example, a PCF can be recorded based on data. This is used to compare and identify critical processes within the company. In order to optimize production with regard to sustainability, the data obtained and processed provides important insights and can be used at various levels along the value chain (see *Figure 3*).

Digital Twin in Production

Already during production planning, a detailed digital twin of the production plant allows a realistic simulation of the processes and can provide information on optimized plant configurations or production line design in the concept phase of new plants [21].

In production control, digitization and networking and the associated permanent and direct communication between machines and control systems offer the opportunity to establish smart and demand-oriented production systems, which will play a central role in future production strategies. Only continuous, cross-supply-chain networking enables the implementation of demand-oriented pull production, in which the production quantity is determined by demand and overproduction is avoided [22], [23].

The generated data basis enables different optimization strategies at the shopfloor level. With the help of the Digital Twin and a processing algorithm, anomalies in production can be detected more quickly and the production of faulty parts can be stopped earlier. The Digital Twin of a production plant enables virtual commissioning and shortens the start-up phase for the start of production or the adaptation of optimized program sequences, whereby the optimum operating point is reached earlier and the efficiency of the plant is increased [21].

Digital Twin until EOL

The full potential of end-to-end data acquisition can only be exploited if it takes place over the entire life cycle of a product. During each phase of the life cycle, critical information is generated that can be fed back into the development of new variants or production concepts. For example, a Digital Twin containing information from the use phase can extend the service life of products by adaptively adjusting maintenance intervals using prediction models. With detailed product information, from raw material extraction to EOL, the feasibility of circular economy increases, as downstream remanufacturing, recycling or rethink processes can be carried out more easily. Automated disassembly can be carried out much more efficiently if, on the one hand, the data from assembly is available and can be used and, on the other hand, it is known what events the product has gone through in the use phase and what changes it may have undergone in the process. In addition, information about the materials used in manufacturing of the product up to the EOL can enable improved evaluability with regard to recycling [20].

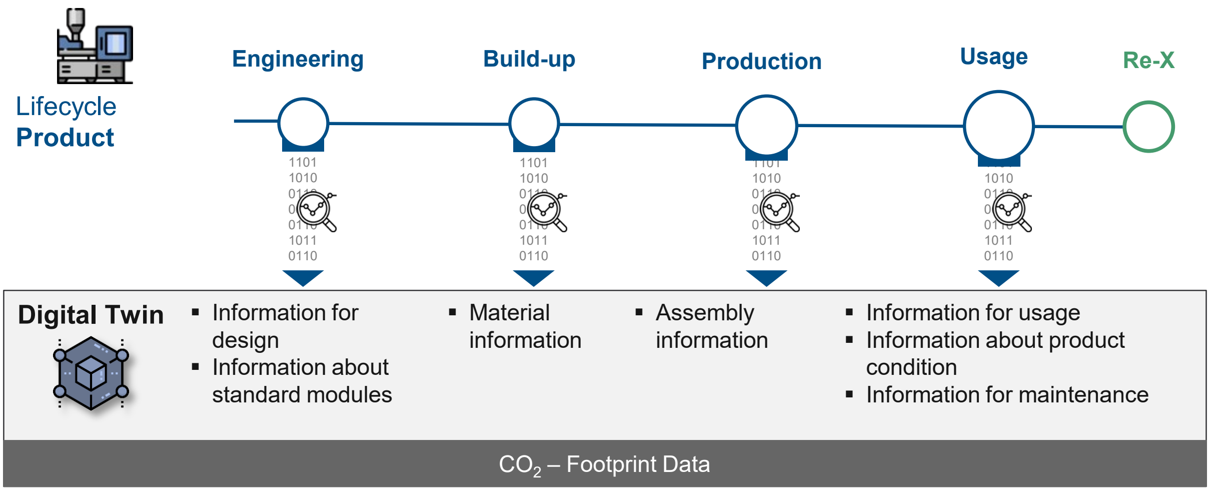

Figure 3: Possible applications of digital twins

3.2 Virtualization

At first glance, the direct connection between virtualization and sustainability may not be obvious, partly because the term is used in many different ways in different domains. Nevertheless, this technology enables companies to react flexibly to demand and to scale resources according to need or to utilize them optimally. In production technology, virtualization often describes the abstraction of production resources, processes and products in order to use digital models for development and optimization [24]. This application can, for example, significantly reduce waste that would normally occur during the start-up and testing of real processes, or optimally utilize machines. In information technology, the focus lies on the abstraction of resources such as hardware, software or the network. Depending on the type of resource to be virtualized, different methods have become established that correlate closely with the respective goals and requirements.

Traditional IT Business Models

The consolidation of several virtual servers on one physical hardware has been a standard procedure in IT for many years in order to make optimum use of the available hardware. In the meantime, many of these applications run in cloud environments, which make it possible to temporarily increase resources such as CPU or RAM as required (e.g. during peak loads). This makes it possible to use the available resources efficiently and in line with demand. For this reason, more and more companies are also striving to virtualize workstation computers. This involves replacing the physical hardware with an energy-saving thin-client that establishes a connection to a server on which the previously locally available computer runs in a virtualized environment. In addition to simplified, central administration and maintenance of the system, the required resources can now be adapted without physically replacing the hardware at the workstation. A practical example shows the savings potential in terms of energy consumption: By consolidating 8 servers and installing 40 thin-clients, the annual energy costs of a company could be reduced by 35,000 KWh [25].

Virtualization in Production

Many of the approaches and methods from the IT sector presented in the previous paragraph can also be transferred to production. However, production-specific requirements, such as the real-time capability of controls and communication channels, must be taken into account. The control panels and screens on the production lines can often be replaced by energy-saving thin-clients, while a full-fledged workstation computer runs in the background. Virtualization of programmable logic controllers (PLCs) is also no longer a pure research subject, but is offered by companies such as Bosch Rexroth, Codesys and Siemens. By consolidating multiple PLCs on one hardware, performance can be scaled flexibly based on requirements. For example, performance can be doubled at the push of a button without swapping hardware if, for example, a "power-hungry" AI model is to run on the controller. In addition, virtualization offers advantages in terms of maintenance, updates and the security of the controller. Due to the fact that no physical hardware exists that is outdated and must be replaced accordingly, the service life of machines can be extended considerably. However, the focus does not always lie on the hardware alone. Frequently, this must also be considered in combination with the network. Companies such as Cisco and Audi are working on virtualizing real-time capable networks, for example on the basis of Profinet [26]. Due to increasing digitization and the use of IT systems in production, virtualization can have a positive impact in all lifecycle phases, as summarized in *Figure 4*.

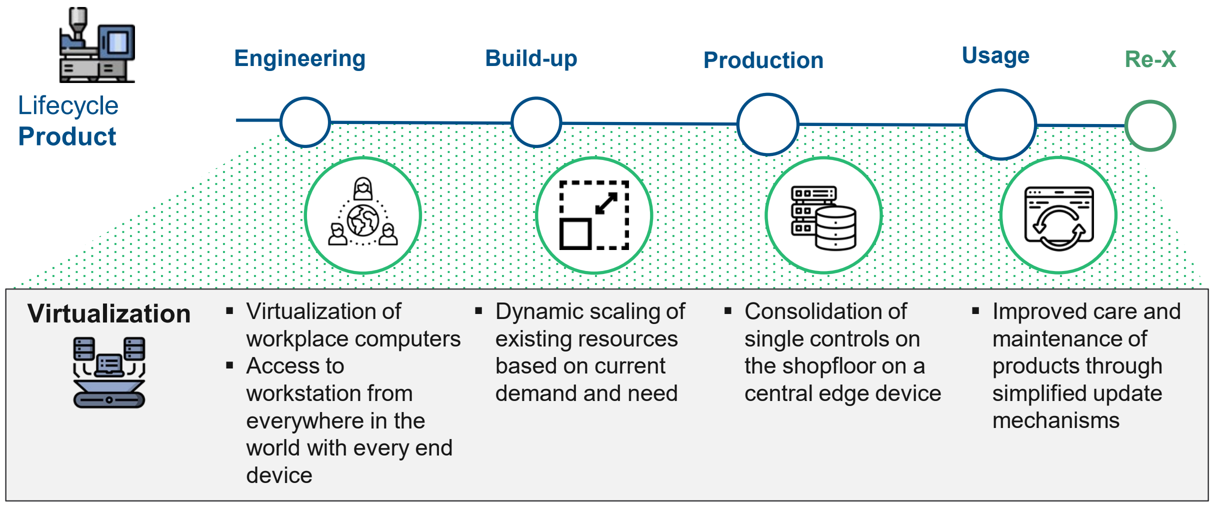

Figure 4: Application possibilities and potentials of virtualization

3.3 Industrial Metaverse

At its core, the broad term "Metaverse" describes an environment where the physical and digital worlds merge [27]. The convergent use of mixed reality technologies in the Metaverse enables multisensory, dynamic interaction with virtual 3D environments, digital objects and people in real time [28]. The Metaverse is generally divided into two areas that offer different potentials for use: While the *Consumer Metaverse* focuses primarily on the further development of social interaction, events and games, the *Industrial Metaverse* offers a wide range of possibilities for the innovative design of domains such as healthcare, education and industry [29]. From a production engineering perspective, there are currently three main areas of application.

Create new Opportunities for Employee Qualification

The Metaverse offers employees more opportunities to learn about new environments, processes and machines [30]. The virtual environment makes it possible to place people in dangerous situations in a controlled and repeatable manner so that they can learn how to deal with them. For example, it is possible to show what happens when a machine tool is operated incorrectly and a crash occurs - without any material or personal damage. In addition, this type of learning offers a certain scalability: Although only one machine can be present in reality, any number of employees can learn how to operate it in the virtual environment. However, in order to approximate the experience in the Metaverse and the experience in reality, further research is needed regarding the enhancement of immersion. Haptic feedback in particular will play a major role in the future.

Improvement of the Engineering Process

CAx tools have been used in the engineering process for years to support the design of 3D visualization to support the design of assets. In the vision of the Metaverse, this support is to reach completely new dimensions: Developers can now not only design products, but also, by means of mixed reality technologies, view them from new angles in the associated environment and, with appropriate kinematicization and simulation, test their functionality. For example, individual workstations and even entire factories can be designed and validated in virtual space before they are built. The first steps towards realizing this vision have already been taken by a number of automotive companies, among others. [31], [32].

In addition to 3D visualization, an exchange between different actors in real time is also a target that can significantly increase productivity: In established workflows, data from different tools usually has to be manually merged and adjusted. Currently available platforms for the implementation of the Industrial Metaverse promise to break down these limits in order to realize a more transparent use without interface losses and compatibility problems. [31], [33].

Generation of synthetic Data

The use of computer vision is becoming more and more ubiquitous in the manufacturing industry. In addition to its use for quality control of components [34], it can significantly improve the automated handling of objects in combination with robotics [35]. Regardless of the use case, however, the training of the required machine learning algorithms requires large, labeled data sets, which are often unavailable or difficult and time-consuming to obtain [34]. The Industrial Metaverse offers a solution for this: By means of photorealistic renderings of 3D environments and objects and the possibility to flexibly adjust lighting, object poses and environment, synthetic images or data for training can be created and labeled quickly, easily and even automatically [33]. In this way, production systems can be enabled to function error-free and thus become more sustainable from the very first start-up.

The potential influences of the Metaverse on the various stages in the life cycle of a product are summarized in *Figure 5*.

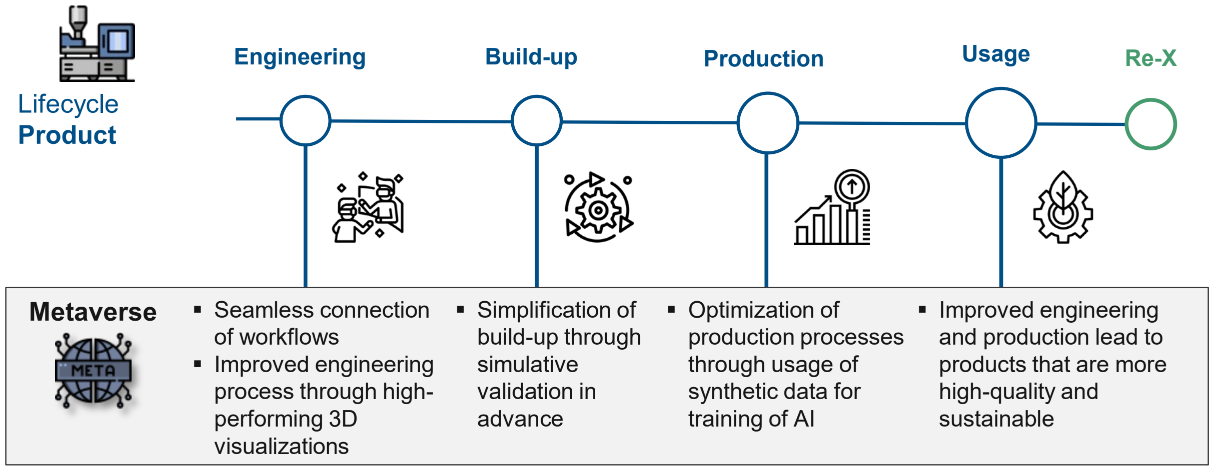

Figure 5: Possible applications of the Metaverse

3.4 Artificial Intelligence for Production Engineering

The application of AI along the entire product life cycle offers companies numerous starting points for increasing efficiency and can contribute to optimizing the sustainability and service life of products. By using AI systems, products can be developed in such a way that their useful life is extended and resource consumption is reduced at the same time. In production, AI systems can help reduce energy consumption and minimize the production of waste. In this way, companies can not only increase their competitiveness, but also contribute to the conservation of resources and the reduction of the ecological footprint.

Quality and Productivity Improvements

AI offers great potential in production to increase productivity and quality while reducing costs. An important aspect of this is the analysis of large volumes of real-time data in order to identify anomalies and patterns, gain targeted insights and derive measures [36].

Predictive maintenance is an exemplary application of AI in production, in which the condition of machines and systems is monitored by means of data analyses in order to detect anomalies and deviations at an early stage and to initiate maintenance and servicing measures. This can minimize unplanned downtime, extend the service life of machines, and reduce the production of defective parts. For example, AI-based tool wear determination can help increase the degree of utilization. Another application is predictive quality, where the quality of products is monitored during the manufacturing process through real-time data analysis in order to react quickly to defects or problems. In addition, AI-based optimization of a machine's operating point can be performed continuously, parallel to the process and according to the context at hand, by determining the optimal machine parameters through data analysis and process optimization models.

Generative Artificial Intelligence

Generative Artificial Intelligence is a subfield of AI in which models previously trained on large amounts of data can independently generate new content, for example for use in use cases for which no real data is yet available. The technology has applications in many areas, such as synthetic image generation, text generation, and automatic modeling of 3D objects. In product development, generative algorithms can be used to optimize the design and its topology with respect to selected target variables. These can be, for example, the lowest possible weight while guaranteeing functionality or the reduction of the required input of raw materials and energy in production [37]. As part of the subsequent commissioning of production processes, synthetic image data can be used to train computer vision models, as described in chapter 3.3. In addition, machines, such as robots, can be programmed and parameterized autonomously through the generative creation of simulation scenarios [38]. Here in particular, the synergies between the approaches of the Industrial Metaverse and the use of generative AI become clear. By using synthetic data, the economic usability of AI shifts towards smaller batch sizes, since no real data is required. In addition, generative algorithms whose training is based on engineering and production information can be used to generate content for information and worker assistance systems. This can provide great added value, especially for untrained personnel in view of structural and demographic change. Despite the numerous potentials of generative AI, the major challenge is to overcome the domain gap and ensure that generated content also leads to robust solutions that can withstand real-world use [39]. Here, research is being conducted on numerous approaches to solving the problem, such as domain randomization.

Human and Artificial Intelligence in Interaction

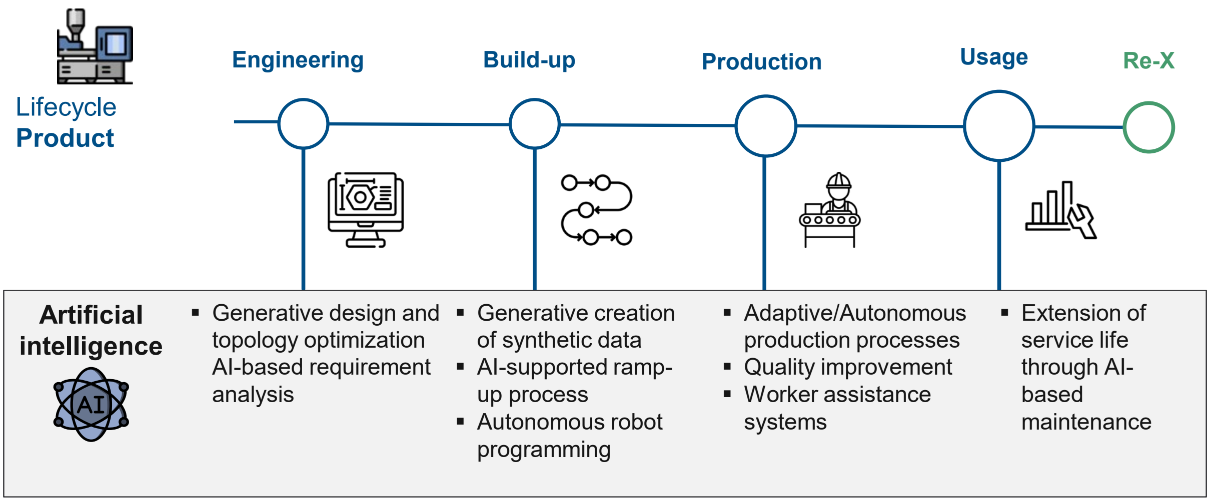

Figure 6: Possible applications of artificial intelligence for production engineering

There are numerous use cases and scenarios in which AI systems offer added value in the sense of gaining insights from data, but in which an autonomous application of these insights, for example in the form of an automated adjustment of machine parameters, is not meaningful. Examples of this are the period in which AI is being trained and is therefore not yet performant, or when process steps are considered in which the use of AI models is not sufficiently robust and comprehensible. In the case of products with a low number of units and a high number of variants, this situation could possibly never be overcome. In order to nevertheless exploit the potential of AI, a system with hybrid intelligence can be used in such cases, in which human and artificial intelligence interact bidirectionally [40]. AI can be trained more efficiently through targeted input from experts, which in turn allows it to be used in human-centric applications [41] can feed back analyses and recommendations for action via assistance systems. *Figure 6* summarizes the described sustainability potentials of the aforementioned AI approaches along the life cycle of a product.

4 Sustainable Production-as-a-Service

In the previous chapter, digital technologies such as digital twins, virtualization, the Metaverse and AI were mentioned as enablers for sustainable production. Although these technologies are already widely available, albeit in varying degrees of maturity, there are still numerous challenges, especially for small and medium-sized enterprises, which prevent them from using these seemingly tangible solutions. The entry barrier seems too high from the customer's point of view, despite the high supply, due to a lack of expertise in the technologies and high initial investment costs. This reluctance is understandable, as the profitability of the technology is often uncertain. At the same time, the sometimes fluctuating customer demand as well as unstable supply chains and the associated production downtimes cause great uncertainties, which stand in the way of long-term investments. As-a-service-based business models can lower this financial and knowledge barrier and potentially give customers broader access to digital technologies. This does not compromise customer expectations as they are more concerned with outcomes, personalization and continuous improvement than ownership and generalization [42].

4.1 As-a-Service in the digital Age

As-a-Service offers two types of contracts: flexible and performance-based [43]. The flexible contract type is about synchronizing revenue and expense streams associated with the variable use of the product. In the performance-based contract type, on the other hand, the value proposition is measured by the impact of the product, e.g., an increase in productivity or a reduction in the total cost of ownership (TCO). In contrast, with a pure product offering, the value proposition lies in the delivery of the physical product and the promised features, without any responsibility over the fulfillment of customer expectations. With aaS, there is a shift from an abstract marketing promise to a value proposition. The ownership structure also differs, as the customer only receives temporary rights to use the product and is thus considered a tenant.

Subscription Models

Subscription and "Pay-per-X" are common revenue models for monetizing aaS [43]. Subscription models generate recurring and stable revenues (e.g., monthly or annually) that can be flexibly expanded through upgrades. However, the resulting customer loyalty can be terminated at any time. With pay-per-X, the customer only pays for the service that is actually used or produced (e.g. pay-per-hour or pay-per-part). Pay-per-X models are often combined with subscription models in order to cushion possible risks such as the loss in value of older machines. In this case, the provider sells the function of the product for a defined period of use via modified sales and payment systems such as subscription, sharing, pooling or leasing [44].

Everything-as-a-Service

The variety of possible services is unlimited: from software (Software-as-a-Service), to computer infrastructure (Infrastructure-as-a-Service), to plant and machinery (Equipment-as-a-Service), all types of assets and services can be offered as services [45]. The term for this approach is Everything-as-a-Service (XaaS). With Software-as-a-Service (SaaS), the use of a software is leased as a service instead of selling the software as a license [46]. This offers the customer advantages in terms of product support and updates, which can be provided automatically. Infrastructure-as-a-Service (IaaS) enables computing infrastructure to be rented on demand, allowing companies to implement one-time applications and absorb peak loads. Continuous monitoring, maintenance and repair is also part of the service to keep the systems and machines in optimal operating condition.

From Data Integration to Smart Services

A key factor in maximizing the success of aaS models is the use of data. With Equipment-as-a-Service (EaaS), important production data can be collected and evaluated through data integration and communication between the plant user and the aaS provider, important production data can be collected and evaluated. As a result, resource and energy consumption can be optimized, plant risks minimized, and plant life maximized in terms of sustainability. End-to-end IT systems are necessary to enable continuous data feedback and analysis. In addition, appropriate skills and methods are needed to analyze the collected data to better understand customer needs. Close involvement of the customer through a participatory approach is thus essential. Data collection also opens up opportunities for data-based digital service offerings, such as the use of artificial intelligence or the creation and use of digital twins. These services are also called smart services. In combination with the appropriate sensor technology on the product, data can be recorded and shared via private as well as public communication channels. Ideally, this makes the company not only a service provider, but also a provider of a digital solution [42]. New business areas can be opened up, whereby the analysis of market trends points the way.

4.2 As-a-Service as an Enabler for sustainable Production

AaS not only offers an opportunity to counter the growing dynamics and complexity of the markets, but also holds considerable potential for achieving the sustainability goals. In particular, SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Change Mitigation Measures) benefit from aaS models, as these are primarily aimed at conserving resources and ensuring that products last as long as possible in the economic cycle [47]. Furthermore, alternative distribution systems such as sharing lead to a higher utilization of products and production facilities, resulting in positive effects in both production and consumption. In addition, XaaS promotes factors such as innovation and infrastructure, which can have positive effects on society.

Equipment-as-a-Service

SYSTEMIQ is a system change company that works for the change to a sustainable economic system [43], [47]. Together with the machine manufacturer Trumpf, the company carried out a quantitative analysis of the sustainability potential of an aaS-based laser cutting machine. The decarbonization potential and the reduction of the TCO were analyzed with the help of two EaaS scenarios: EaaS 1.0 considered a pay-per-part business model that is already available. By using AI-based process optimization or over-the-air updates, further potentials can be raised. In EaaS 2.0, this model was extended by a digital marketplace to bundle customer demand and optimize machine and material flow. These two approaches have the potential to decarbonize metal sheet manufacturing by 37% and 65%, respectively, and also enable customers to reduce TCO by 16% and 24%, respectively (see *Figure 7*). The main influence was the optimization of material waste, which calls for new ways of digital procurement processes with higher freedom of order placement and disassembly.

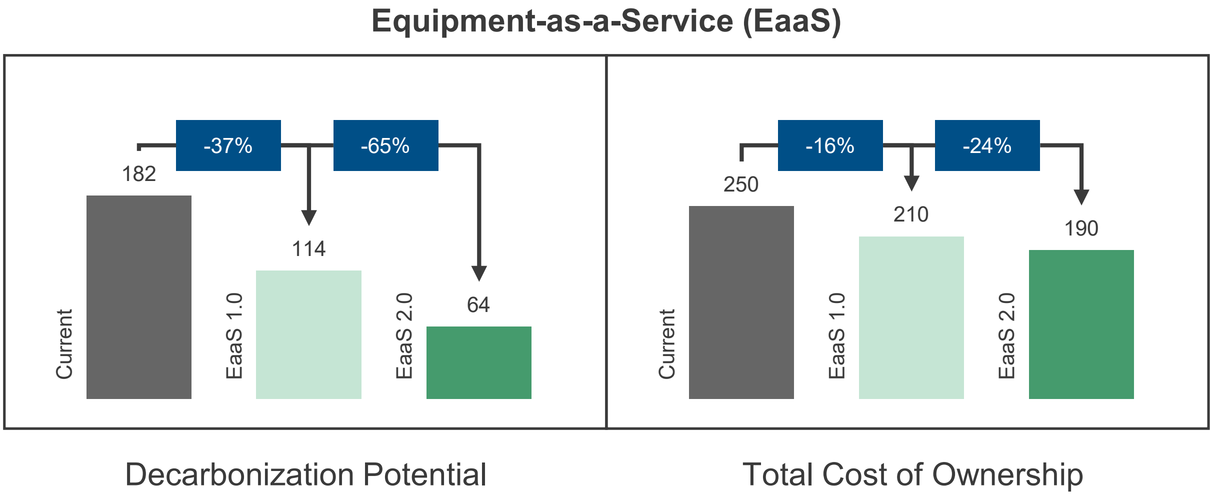

Figure 7: Sustainability potential through Equipment-as-a-Service. Source: SYSTEMIQ/Trumpf

In aaS models, companies retain ownership of their product and responsibility for its life cycle. This motivates them to strive for circular business models. The transformation to an aaS business model requires a circular product design and operating model. This means that a product must be designed and developed for long life and quality. By combining the presented digital technologies and the aaS models, the concept of Sustainable Production-as-a-Service can be realized. *Figure 8* summarizes the components of this approach.

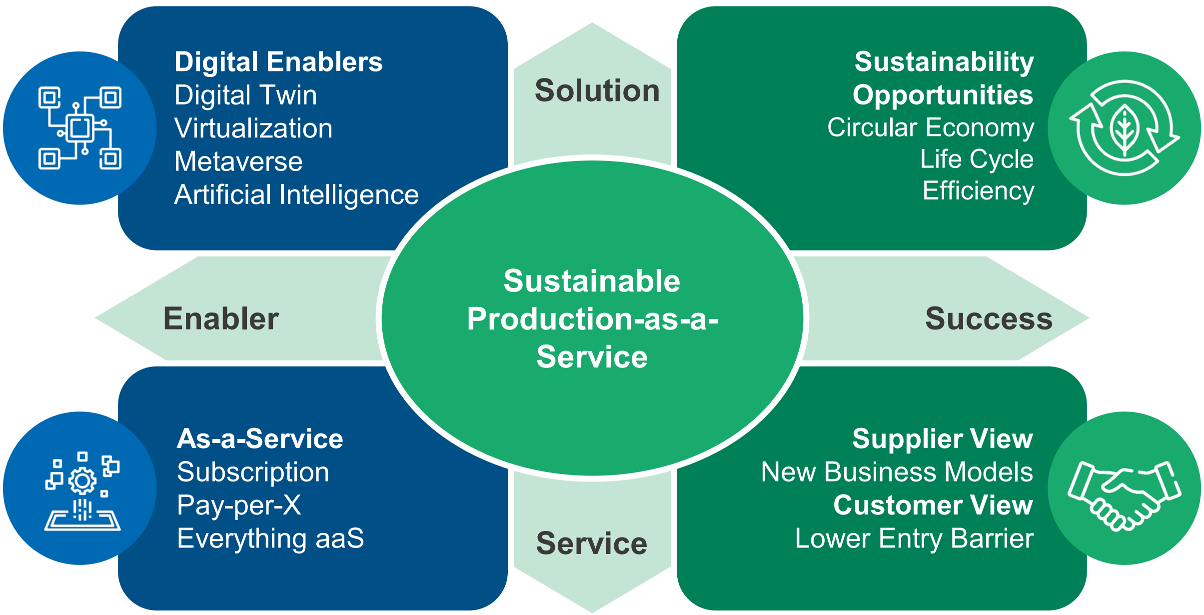

Figure 8: Sustainable Production-as-a-Service

5 Examples from Industry and Research

The previous chapters have shown that the use of digital technologies and as-a-service models can be enablers for sustainable production. In this chapter, several examples will be used to compare the previously explained, partly conceptual approaches with specific success stories from industry and research. For example, the Autopilot research project (BMBF, FKZ: 02J21E000) is investigating how (vehicle) production can be made more sustainable through the use of adaptable manufacturing cells and recyclable resources. In particular, the design of the Equipment-as-a-Service business model is being examined using the example of wooden landing gear (Chapter 5.1) and modular clamping devices (Chapter 5.2). The ViRTNC research project (BMWK, IGF project: 22716 N/2) shows the potential of virtualization using the example of NC controls (chapter 5.3). Furthermore, the potentials of the Industrial Metaverse are presented by means of an example from industry (chapter 5.4). Finally, an application example from the research project GeMeKI (BMBF, FKZ: 02P20A121) shows the opportunities of hybrid intelligence in final assembly (chapter 5.5).

5.1 Charge Carrier-as-a-Service

The start-up Ligenium from Chemnitz is a spin-off of the TU Chemnitz and offers digital and climate-neutral logistics solutions based on wood-based materials. Particularly noteworthy is the charge carrier, which enables a 50% tare saving compared to steel constructions while maintaining the same load capacity and larger load volume. Thanks to the modular plug-in connection design, a low dead weight and intermediate storage volume and a high degree of reusability are guaranteed. The wooden charge carriers are characterized by climate-neutral recycling, since wood binds CO_2 and demonstrably improves the CO_2 balance. The higher resistance of wood under chemical and aggressive environmental conditions compared to metal constructions enables an extension of the life cycle. Due to the special low maintenance and intralogistic load capacity, the charge carriers made of wood materials are an environmentally friendly and long-lasting alternative.

This example already shows that the issue of sustainability plays a decisive role in engineering. The choice of alternative materials can have a direct positive impact on the CO_2 footprint, and the modular design facilitates repairability and thus leads to extended use. This provides an optimal starting point for new business models, such as equipment-as-a-device or, in this case, load carrier-as-a-service. The customer only pays for the equipment as long as it is actively used in production. When the equipment is no longer needed, it is returned to the manufacturer. The manufacturer must then decide, based on the previous use of the resource, which R-strategy (see section 2.2) is best for continuing to use the resource optimally in terms of the circular economy. From the supplier's point of view, it is desirable to continue renting out resources with as little effort and adjustments as possible. To this end, all relevant data must be recorded throughout the various life cycles and made available as a basis for decision-making. For this purpose, the load carrier requires sensor technology that continuously records environmental conditions such as temperature and humidity as well as loads. Reliable connectivity is of great importance, especially for mobile equipment, in order to ensure the required data continuity.

5.2 Clamping Device-as-a-Service

The EDAG Group is the world's largest independent engineering partner to the mobility industry. It handles strategy development through the concept phase and series production to production planning and optimization for vehicles and production facilities. Within the EDAG Group, EDAG Production Solutions GmbH & Co. KG supports the implementation of smart factories and has developed, among other things, the UniSerienStandard®.

This operating equipment standard includes flexible fixtures that enable fast and repeatable joining of workpieces. Particularly noteworthy is the modular structure of the equipment standard and the drawing-free production according to 3D CAD data. The modular design allows high flexibility, short delivery times (approx. 35% faster than OEM series) and low costs (approx. 32% cheaper than OEM series). At the same time, a reduction in mass of approx. 40% with improved strength can be achieved, which results in a significant reduction of the CO_2 footprint. The fixture components consist largely of standard parts, which ensures a high degree of reusability in subsequent projects. The design of the UniSerienStandard® reduces the number of individual parts required and the modular structure favors the repair and recycling of the fixture. This high modularity is particularly advantageous for prototype construction. The further development of an electro-pneumatic setup reduces the number of wiring schemes and thus additionally reduces the carbon footprint. This also makes it possible to record usage data to track the usage history of the fixture. This is advantageous for reusability, as a prediction can be made about the service life.

Again, this shows that the modular design of the fixture is a key enabler. Many companies have so far avoided this approach in engineering due to the increased effort and resulting costs. However, since the equipment remains the property of the supplier and changes several times over its lifetime, the initial effort is worthwhile when considered over the entire lifetime. In addition, modularization offers the advantage that the engineering process can be partially automated, which has a positive effect on delivery times and thus on customer satisfaction. By feeding data back into engineering, improvements can also be made to the equipment itself.

In the previous sections, the technical challenges in designing the business model were discussed in particular. These challenges are also partly due to organizational factors. Internal company policies and standards, for example, can be a significant obstacle because they are not recognized across the industry and thus may not match the standards of other users. This can limit reuse despite the same function. Therefore, it remains to be determined whether users are willing to deviate from their own standards in order to reap the benefits of reduced fixture costs and more sustainable use, or how fixtures can be designed flexibly without compromising existing standards. Currently, fixtures can only be leased. However, this model can be extended to an EaaS model to capture the benefits mentioned in the previous chapter. *Figure 9* summarizes the advantages of EaaS once again using the example of ligenium and EDAG PS.

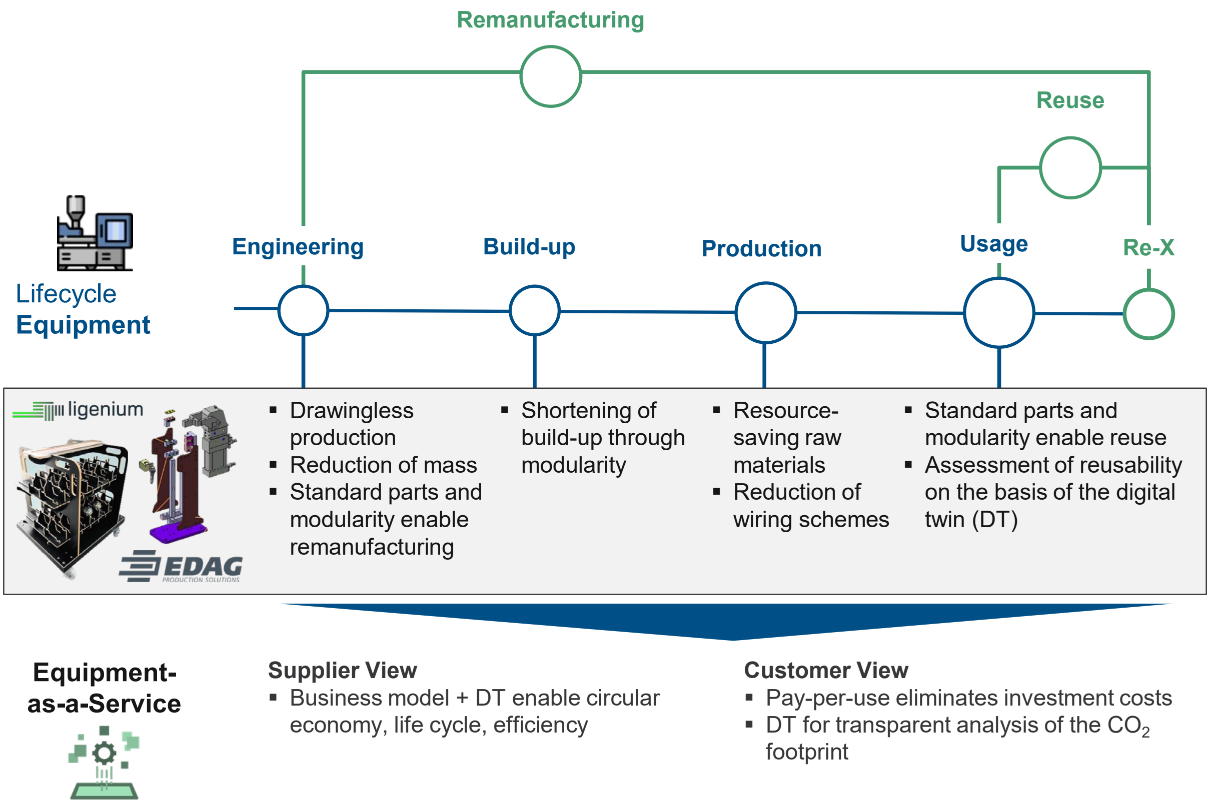

Figure 9: Equipment-as-a-Service using the example of ligenium and EDAG PS

5.3 Real-time Virtualization of an NC Controller

In the ViRTNC project (real-time virtualization of an NC control for dynamic provision of hardware resources for computationally intensive control algorithms), the aim is to investigate systematically how the virtualization of NC controls for machine tools can succeed (see *Figure 10*). For this purpose, first an analysis of the real-time requirements of NC controls is performed, then a virtualization environment is conceptualized and set up before the virtualized position control of a single drive is implemented. On the basis of this, compensation mechanisms in the position control can then be researched, which make robust control possible despite disturbances due to occurring latency and jitter. In addition, concepts for the orchestration and information-technical protection of the virtualized controllers will be developed with the help of the participants of the project committee. The project is accompanied by the construction of a demonstrator in the form of an exemplary machine tool, which is used for the final evaluation and validation of the developed concepts.

The realization of a real-time capable control system is a challenge that should not be underestimated in the virtualization and consolidation of industrial control systems. In general, the so-called hypervisor, which forms the abstracting software component between the server hardware and the operating systems of the controllers, causes additional latency that does not occur with conventional PC-based control systems. To counter this problem, the ViRTNC project uses a hypervisor that has been optimized for real-time capability and configured accordingly. This hypervisor can already guarantee scheduling latencies of a few microseconds in virtualized controllers. In addition, however, communication with field devices in real time is also necessary for the intended overall system to function. Analogous to the use of commercial hardware from the IT sector on the server side, commodity hardware should also be used as far as possible with regard to the network components. Therefore, it will be evaluated to what extent prioritization mechanisms and standard Ethernet can enable sufficiently low-latency communication between edge servers with virtualized controllers and field devices. In addition to the realization of the physical network based on commodity switches, different concepts are analyzed to realize the virtualized network within the edge server in software or hardware. For a realistic evaluation of the real-time capability of the overall system, measurements of the response time at digital input and output terminals are performed. Concepts and implementations developed in the project so far have reached a response time in the range of one millisecond. In the further course of the project, an NC controller will be virtualized and used to control a real machine.

Extension through Pay-per-Function

Extending this approach with switchable functions offers the customer increased flexibility and the use of current solutions, such as in the area of artificial intelligence. This could be realized through a pay-per-function model, which is possible on the basis of virtualized hardware.

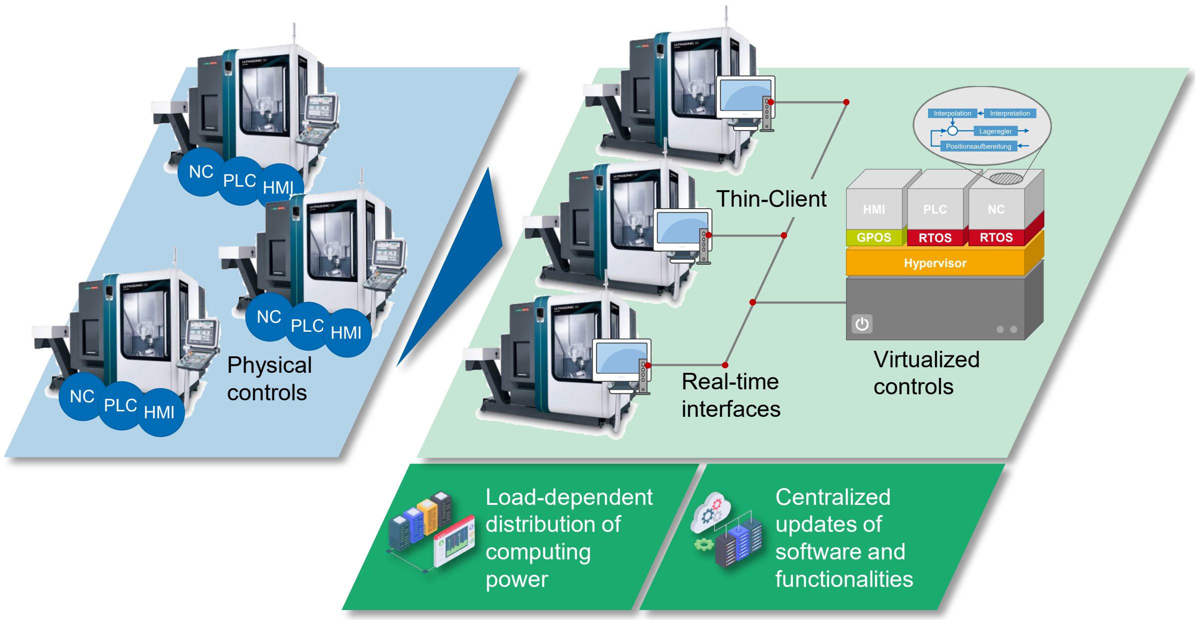

Figure 10: Potentials through real-time capable control virtualization

5.4 Application of the Industrial Metaverse

In cooperation with the Boston Consulting Group (BCG), Amazon Web Services (AWS) and Nvidia, the Automation and Control Technology department of the WZL has already gained initial experience in the use of the Industrial Metaverse for addressing production engineering issues. The following use case was considered: In the production of vehicles, the cockpit is usually mounted as a coherent assembly in the car body. The surfaces of the cockpit (e.g. the leather covering of the dashboard) must not show any scratches or other damage. Computer vision systems based on machine learning methods are used to detect possible optical defects. To train these methods, large, labeled data sets are required, which can be generated in the described scenario by creating numerous images of intact and defective cockpit surfaces. In practice, this means that when a new production line is commissioned or a new cockpit optic is introduced, there is not yet a sufficient database to reliably identify defective areas. As already described in chapter 3.3, the Industrial Metaverse offers possibilities to solve this problem: By creating a photorealistic 3D model of the production environment and the cockpit, the required images for training the computer vision system can be generated synthetically. The Omniverse platform de-veloped by Nvidia was used in this project to realize the 3D model. The system architec-ture built up in the process is shown in *Figure 11*. By using the uniform file format Univer-sal Scene Description (USD), Omniverse enables a bidirectional, manufacturer-inde-pendent collaboration of different programs necessary for the design of the 3D model. Thus, the current states of the engineering process of the cockpit can be visualized to-gether with the simulation of the production line in a factory environment. Changes in the design of the cockpit or in the processes of the production line can be seen in real time in the combined scene. The 3D model created in this way can now be used to create the necessary image files. State-of-the-art ray tracing technologies support this process with a realistic representation of light and reflections on surfaces. As part of its Omniverse platform, Nvidia already offers programming tools to accelerate and partially automate the process of synthetic data generation.

This example shows how the Industrial Metaverse can contribute to the optimization of production lines and thus also to increasing sustainability. In addition, the potential for using the as-a-service idea is also found here: The provision of platforms for implementing

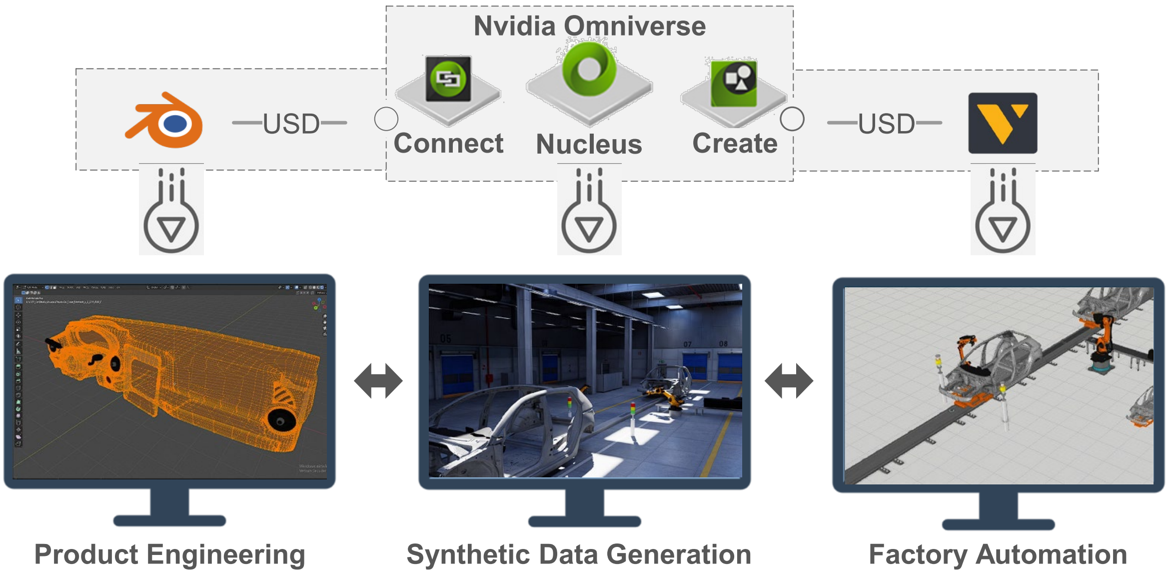

Figure 11: System architecture for the implementation of the Industrial Metaverse

the Industrial Metaverse as well as the completely external creation of synthetic data can be derived as a possible business model. Companies that do not have their own employ-ees with knowledge of the necessary programs can purchase the required expertise and the resulting results flexibly and in line with their needs.

5.5 Hybrid Intelligence in electric Motor Assembly

Industrial assembly usually has a low degree of automation in the case of high process complexity and low or still unclear unit number potential. As part of the BMBF-funded research project GeMeKI (Generalization of Human-Centered AI Applications for Produc-tion Optimization), an AI application is being examined in the manual small-series assem-bly of electric motors at Miele, in which the bearing points of the rotors are glued into the stator housing by hand. This is a quality-critical process in which the automatically applied adhesive bead is subjected to a visual inspection by specialist personnel after dispensing. This inspection is necessary because the quality of the adhesive bead and the joining process varies depending on numerous influencing variables such as environmental parameters (e.g. temperature, humidity, solar radiation), time influences (e.g. wear, flow time, storage time) and machine parameters at the metering and pressing station.

In order to support the workers in this multifactorial process and to accelerate the training process of unqualified employees, a system with hybrid intelligence is set up as shown in *Figure 12*. For this purpose, relevant parameters are recorded by sensors and stored in a workpiece-specific manner with camera data of the gluing bead. In order to generate suitable data for teaching a reliable assistance AI, the workers label all data sets recorded during normal operation with an OK or not OK statement after visual inspection of the gluing bead. In the case of a not OK glue bead, a defect category and the measure taken to rectify the defect are also specified and stored. On the basis of this data, an AI-based assistance system is created which is trained by the specialist personnel and which provides the employees with process-parallel predicted quality statements on the recorded glue bead, a classification in the case of not OK defects and recommendations for improvement measures. forecasts as well as recommendations for improvement measures via a dedicated user interface. Through continuous interaction with the intelligence system, the AI is optimized beyond the initial training phase so that a continuously growing reduction of rejects and an improvement of product quality can be achieved. This reduces the waste of resources and extends the product life.

In addition to the human-centered development, implementation and introduction of all AI components and interaction interfaces, the main focus of the project is to achieve the highest possible transferability of all developed solution modules, whether hardware or software. This should enable economic reuse in other assembly lines, at other locations and for other products. Modular solution modules developed by the project partners should be easy to adapt for a wide range of applications and be combinable for downstream use in digital composite products of several partners.

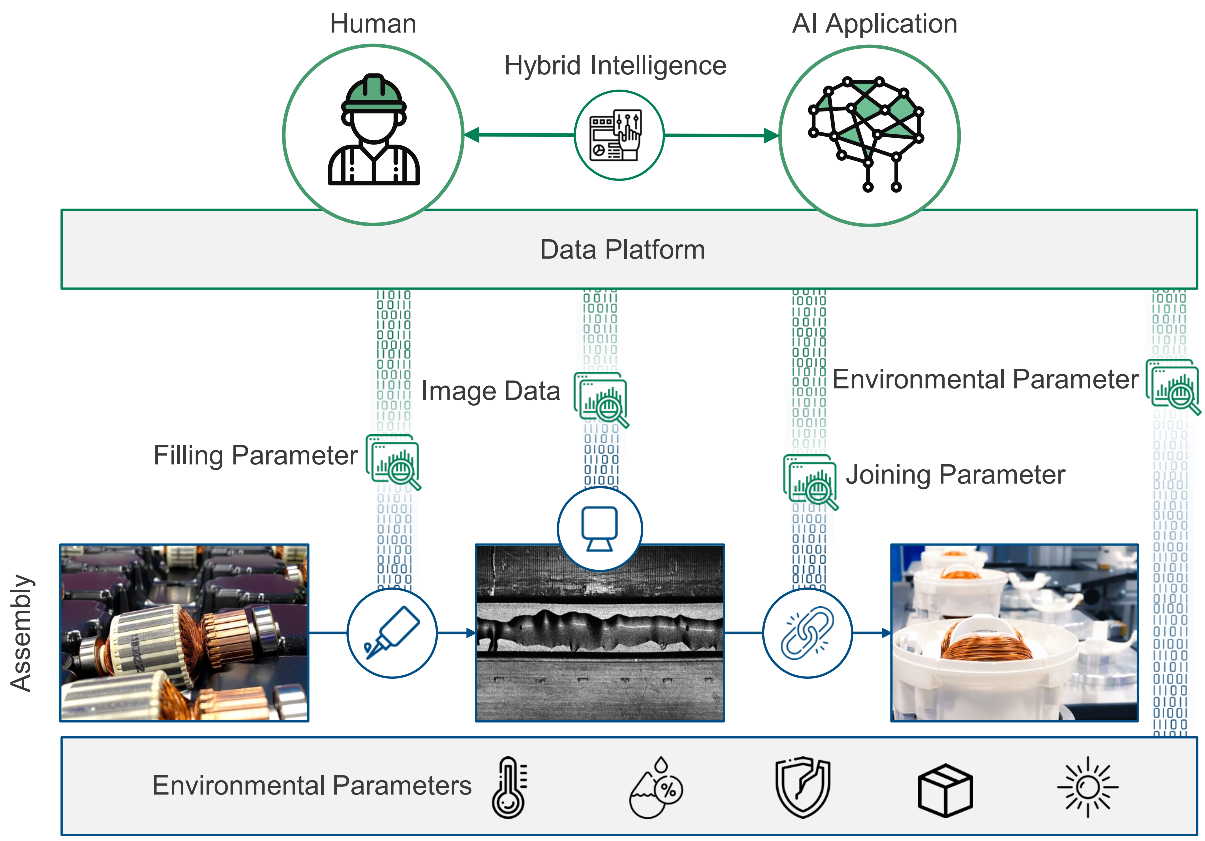

Figure 12: Hybrid intelligence in Miele's electric motor assembly line

Digital Composite Products with as-a-Service Components

Digital composite products are made up of several modules of different types, sizes and tasks, each of which is contributed by different partners specializing in a particular area. As a rule, there is a hardware system, e.g., a machine or plant, and one or more software modules (microservices) that digitally extend the functional spectrum of the hardware. In the case of the AI-based assembly assistance system, the hardware system is an automation cell from automation specialist Xenon equipped with camera technology, which is supplemented by a quality prediction AI developed by industrial AI supplier aiXbrain.

For joint exploitation beyond the scope of the project, a joint business model is needed that offers all partners an economic incentive and at the same time secures their sovereignty over the respective contributed components. Contributing modular components in a commercial and technical as-a-service model is ideally suited for this case, especially for those partners who contribute digital modules to extend functionality. Consistently, an AI supplier like aiXbrain therefore also offers its products as software-as-a-service, using the subscription + pay-per-X model described in Section 4.1. The as-a-service model thus becomes the glue for novel digital composite products that can solve the major challenges around sustainable production differently and, presumably, better.

6 Summary and Outlook

This paper presents approaches to implement a circular economy, to extend the life cycle and to increase efficiency with regard to sustainable production. Digital technologies such as digital twins, virtualization, the Metaverse and artificial intelligence are identified as enablers to leverage these potentials. For small and medium-sized enterprises in particular, however, the application of these technologies still represents a major challenge. The sometimes high investment requirements and the frequent lack of the necessary expertise inhibit companies in their implementation. At the same time, fluctuating customer demand, unstable supply chains and the associated production downtimes require a certain degree of flexibility and agility.

Sustainable Production-as-a-Service offers the digital solutions "as-a-Service" to provide customers with a wide range of digital technologies, physical assets and related services to find an optimal solution. By returning the product after its life cycle or use cycle, the provider can refurbish the product or individual components in line with the circular economy and feed it into the next use cycle. Alternative distribution systems such as machine sharing also enable higher utilization of products or production systems. While aaS-based solutions enable customers to bridge short-term interruptions in business operations, they also open up opportunities for suppliers to tap into new customer groups.

The concept of Sustainable Production-as-a-Service was presented using two examples, which offer the charge carriers and clamping systems as an as-a-service model. In addition, three projects from WZL research are used to illustrate how the digital technologies mentioned can leverage sustainability potentials in production in combination with the as-a-service model.

Approaches for the Future

The solutions presented here require holistic data collection over the entire life cycle of a product in order to exploit the potential of the circular economy. This requires uninterrupted data collection along the value chain and, above all, networking between companies and cooperation between users. In particular, competitive thoughts between companies and security concerns of users are opposed to this required networking and transparency. The former requires companies to develop a sustainability mindset and to recognize that opening up can also benefit their own business. The willingness to embrace innovation and change are prerequisites for sustainable production.

7 Literature

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3.3 Quantification of Sustainability Impact

T. Bergs, P. Niemietz, T. Kaufmann, D. Gelbich, J. Mayer, J. Moon, J. Gerhard, A. Peters, F. Seiferth

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Abstract

Quantification of Sustainability Impact

The global economy's sustainability has become a critical aspect for politics and economic investments, with the UN 2030 Agenda for Sustainable Development outlining specific targets and indicators for sustainable development. While CO_2 reduction is a primary focus, other goals such as water management or social goals must be considered. However, understanding the interaction between sustainability targets and indicators is complex. The complexity of sustainability impact of technology or measure can be illustrated by recent example in the automotive steel supply chain. Here, the current impact on energy consumption and carbon emissions are high, and therefore, innovative technologies are needed to support the transition into a sustainability focused supply chain. Simultaneously, the industry is undergoing tremendous changes that impact traditional business models due to the shift to either production of sustainable products, or implementation of sustainable operations. The consideration of an example in material data acquisition, utilization and sharing to enhance collaboration throughout supply chain and reduce waste shows the current of complexity of assessing the introduction of such approaches on a broader scale. Yet, due to the difficulties to quantify the actual impact of a measure or technology, decisions on transitioning to sustainable operations must be based on intuition rather than a concretely quantified sustainability impact, as assessing these impacts is currently beyond available capacity. Innovation decisions must consider personal responsibility for the sustainability of production and the economy.

Kurzfassung

Quantifizierung der Auswirkungen auf die Nachhaltigkeit

Die Nachhaltigkeit der globalen Wirtschaft ist zu einem kritischen Aspekt für Politik und Wirtschaftsinvestitionen geworden, wobei die UN-Agenda 2030 für nachhaltige Entwicklung spezifische Ziele und Indikatoren für nachhaltige Entwicklung festlegt. Während die CO_2-Reduktion aktuell ein primärer Fokus ist, müssen auch andere Ziele wie Wassermanagement oder soziale Ziele berücksichtigt werden. Die Wechselwirkung zwischen Nachhaltigkeitszielen und Indikatoren zu verstehen, ist jedoch komplex. Die Komplexität der Auswirkungen von Technologien auf die Nachhaltigkeitsziele kann anhand eines aktuellen Beispiels in der Automobil-Stahl-Lieferkette veranschaulicht werden. In dieser Branche sind der Energieverbrauch und die Kohlenstoffemissionen hoch, und daher sind innovative Technologien erforderlich, um den Übergang zu einer auf Nachhaltigkeit ausgerichteten Lieferkette zu unterstützen. Gleichzeitig durchläuft die Branche enorme Veränderungen, die traditionelle Geschäftsmodelle aufgrund des Übergangs zur Produktion nachhaltiger Produkte oder der Umsetzung nachhaltiger Betriebsabläufe beeinflussen. Die Betrachtung eines Beispiels für die Erfassung, Nutzung und gemeinsame Nutzung von Materialdaten zur Verbesserung der Zusammenarbeit entlang der Lieferkette und zur Reduzierung von Ausschuss zeigt die derzeitige Komplexität bei der Bewertung der Einführung solcher Ansätze im größeren Maßstab. Aufgrund der Schwierigkeiten, den tatsächlichen Einfluss einer Maßnahme oder Technologie zu quantifizieren, müssen Entscheidungen über den Übergang zu nachhaltigen wirtschaften auf Intuition anstatt auf konkret quantifizierte Auswirkungen basieren. Innovationsentscheidungen müssen die persönliche Verantwortung für die Nachhaltigkeit von der Produktionsunternehmen berücksichtigen.

1 Introduction

In recent years, the sustainability of the global economy has become a critical aspect for future decisions in politics and increasingly for economic investments. The goals for a sustainable development have been defined in the **UN 2030 Agenda for Sustainable Development** which builds on 169 individual sustainability targets and 231 indicators to measure them [1]. If countries in a larger and companies in smaller scale want to contribute to these goals, it is important to know which measures that can be taken now will affect future sustainability. This is important not only focused on CO_2 emissions but should also take targets and goals such as water management or social aspects into account. However, the understanding of the interaction between all sustainability targets and indicators itself is a complex and ongoing field of research with open questions [2], which makes the reference to concrete measures even more difficult.

For companies worldwide, the sustainability efforts are driving a change towards more sustainable technologies, which raises the question on how to assess the contribution of a given technology to the sustainability targets in the long run and a broader scale. This is especially true for technologies that potentially impact not only local operations of one company but might transform whole value streams. The goal of this article is to raise awareness for the complexity of the quantification of sustainability impact and the implications for companies today based a concrete example in the automotive sheet metal processing industry which is presented in the following.

The automotive steel industry is one of the largest metal processing industries with a strong focus on quality and reliability while being intensely cost sensitive [3]. Here, the need to transition into sustainability driven value chains leads to shifts to sustainable products, e.g., powertrains based on fuel-cells or purely electric, as well as the shift to sustainable operations. Today, this shift together with additional disruptive movements listed below requires the whole supply chain to transform and invest in new technology under increasing uncertainty (see Figure 1):

1. **The transition to a green economy.** As steel production is one of the largest emitting industries in Germany, the transition to an environmentally friendly steel production process has been pushed by politics. Additionally, the increased use of scrap metal to reduce the carbon footprint is advocated by industry associations. While both measures have a positive impact on emissions, they potentially impact steel supply chains by impaired material quality.
2. **The demographic change.** The changes resulting from the retirement of the baby boomer generation pose a major challenge to the manufacturing industry. The loss of workers and their important experience-based knowledge as well as the change in skill requirements for employees through the introduction of digital technologies are leading to a shortage of skilled workers and impair the flexibility of production companies.
3. **The diversification of powertrains in the automotive industry**. The shift in the automotive industry toward electrification and alternative drive systems is leading to a change in the product groups in demand. Sheet metal processing companies are under pressure to develop new product groups within the production of new powertrains. This may require existing processes to be adapted and new technologies to invest in to meet the changed requirements [4].

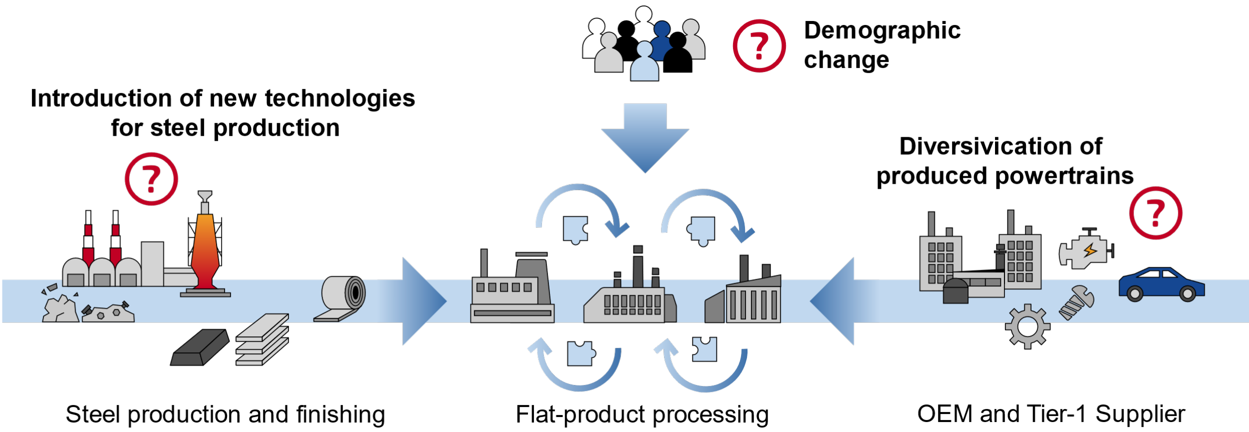


Figure 1: Current situation in the supply chain

All three require the industry to be more resilient and adaptive when it comes to products or the processing of semi-finished products such as metal flat products. The technology considered by this paper is focusing the information gap for the processed materials in the sheet metal supply chain. Currently, the data specifications for flat products are sparse while faults caused by material problems occur regularly and unexpectedly. However, the sparse information renders a preventive adaption of process parametrization or detection of issues difficult. Measuring mechanical properties continuously in production and sharing this information across companies can enable a data-driven alternative to current trial-and-error, experience-based approaches. This eventually enables the shift to explicit knowledge that can be transferred and shared through the workforce more easily than experience-based tacit knowledge.

To understand the difficulties the industry is currently facing, Chapter 2 outlines important shifts in the production of raw steel impacting downstream processes such as sheet metal processing and their influence on the supply chain. Next, three current deficits in the industry are outlined in Chapter 3, followed by the description of the technical solution, intermediate results and a vision of how it could transform the industry in Chapter 4. The final Chapter 5 concludes with an overview of concrete barriers to the integration of new available technologies in Germany.

2 Sustainability Measures that Impact Sheet Metal Supply Chains

This chapter presents some of the most important changes in the manufacture of steel flat products and discusses their impact on subsequent process steps in the supply chain.

2.1 A Sustainable-Driven Perspective on the Steel Industry

The beginnings of the German steel industry date back to the 19th century when the country rose to become one of the world's leading steel producers [5]. In 2020, Germany recorded the highest number of employees in the European steel industry, with around 83,200 workers, which contributed significantly to the gross domestic product of the Federal Republic [6]. The production of steel products is a complex process and involves several process stages from pig iron extraction, shaping and finishing to fine-tuning the mechanical properties of the resulting semi-finished product [5]. The steel industry is at the same time associated with high CO_2 emissions, as it currently requires the use of large quantities of fossil fuels. In 2020, according to the EU statistics office [7], the German steel industry caused around 48 Mt CO_2 equivalent and holds the largest share of industrial emissions in Germany at around 28% [8]. Although emissions in general have been reduced significantly and by almost 40% since 1990 [9], the further processing of steel as well as the production and assembly of steel components, particularly in the automotive industry, continue to make a significant contribution to the sector's CO_2 emissions. Between 2017 and 2020, an average of 40 Mt of steel was produced, of which 26% was for the automotive industry, 11% for mechanical engineering, 9% for pipes, and 12% for smaller steel products [10]. The German steel industry is currently caught between its economic relevance and its negative environmental impact and is under pressure from the new focus on sustainability.

2.2 Using Technology Innovation to Reduce the Footprint in Steel Production

The blast furnace-converter route, also known as the integrated route, is the most common method of steelmaking in the world. It begins with the fact that only the coarser lump ores can be used directly from the ores mined in the mines (lump ore, fine ore). Fine ores must first be agglomerated into either pellets or sinter before they can be further processed. [11]. Afterwards they are transported to and fed in the blast furnace plant. Inside the furnace they are heated to more than 1,500 °C. As a result of the high temperatures, reactions occur and pig iron is produced as well as a waste gas, the blast furnace gas. The pig iron produced in the blast furnace is then processed into crude steel in a converter. In the converter, the pig iron is heated to a temperature of at least 1,500 °C and oxygen is blown into the vessel through a lance. The melt produced by the oxygen smelting process undergoes further secondary metallurgical treatment, which adjusts the temperature as well as composition of the melt, by adding alloying elements and removing by-elements such as sulfur. The melt is then processed in a continuous casting machine, where it is poured into a mold and cooled to solidify into a semi-finished product.

Direct reduction with hydrogen gas (HDR), on the other hand, is a steelmaking method that uses hydrogen gas instead of coal to reduce iron, known as direct reduced iron (DRI). This process is not new but is not currently used extensively in the industry. In the HDR process, iron ore is fed into a reactor where it is heated and exposed to hydrogen gas. Hydrogen reacts with the iron ore and reduces it to high-purity iron. The direct-reduced iron is then further processed to produce crude steel. Steelmaking via the HDR process is considered a more sustainable and environmentally friendly alternative to the traditional blast furnace process (see Figure 2). This process is carried out at temperatures below the melting point of iron (< 1000 °C), which also saves significant energy costs [12]. In addition, significantly lower emissions of CO_2 and other pollutants are emitted during the process. Unlike other methods, electrolysis involves the splitting of water (H_2O) into oxygen and hydrogen [12]. Currently, after direct reduction, the product together with an increased scrap content is added to an electric arc, which produces crude steel using electrical energy.

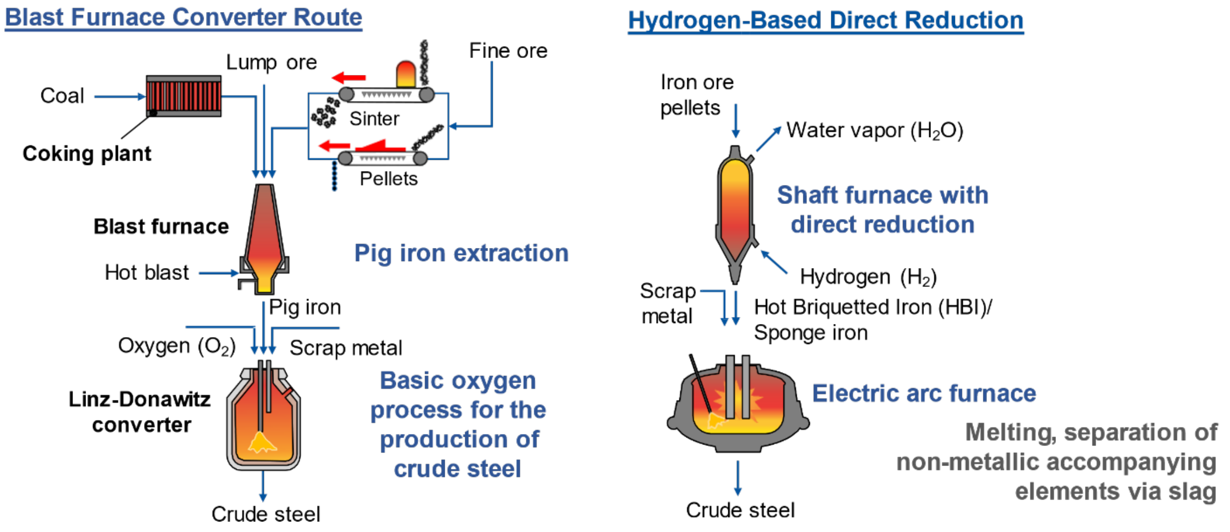


Figure 2: Comparison of the process routes for steel production [13]

However, the implementation of hydrogen-based steel production is also challenging due to factors such as the high cost of hydrogen production through water electrolysis. A change in the process chain for crude steel production can have significant impacts for companies in the supply chain, as the change in process can entail costly requalification measures at OEMs and processing companies. Therefore, steelmakers must not only invest in new equipment and infrastructure, but also in new approaches [14] to scale the process and adjust it so that the quality of the final product competes with current standards [15].

2.3 Increased Usage of Scrap Metal

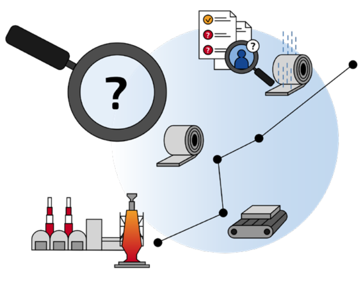
While the introduction of hydrogen-based steel production is already a challenge, developed countries are discussing to increase their use of scrap metal to reduce their dependence on imported raw materials. Based on the latest available data from 2019, the EU-28 was the world's largest exporting economic bloc of steel scrap with an export volume of 21.79 Mt, according to the S&P Global Commodity Insights [16]. Germany itself is one of the largest exporting nations of scrap metals, mainly to the EU, the United States and China [17]. The European steel association EUROFER believes that the scrap currently exported could be processed within the EU to meet the EU's high environmental standards [18]. Recycling of steel scrap potentially reduces dependence on fresh iron ore, minimize overall production costs, and significantly reduce CO_2emissions through numerous recycling cycles [19]. However, despite these benefits, the use of scrap metal was limited according to the Steel Industry Facts 2020 publication, with only about 30% of raw steel comes from scrap metal, while 70% of raw steel originates from pure ore [10]. Yet, for manufacturing processes such as deep drawing, a high degree of flat product purity is required, which cannot always be guaranteed when using high scrap rates [20]. In addition, there is currently no efficient solution for how to remove alloying elements such as cobalt, copper, and chromium. However, contamination by these elements has a drastic impact on the quality of the resulting flat product.

2.4 Challenges of Current Steel Manufacturing and Processing

The increased use of scrap and the introduction of a hydrogen-based manufacturing method are necessary for the transition to a more resource-independent and sustainable steel industry. Both trends affect the production of high-value steel flat products, which are currently produced in high volumes using traditional carbon-intensive blast furnace processes. For the sheet metal processing industry, the transition to a green steel economy means that a change in the composition and setting of mechanical properties of steel flat products for the sheet metal processing supply chain must be expected.

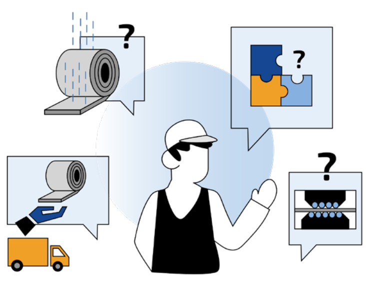
3 Deficits of Material Data Usage in Sheet Metal Processing

A fundamental requirement to define knowledge-based workflows is the availability of explicit and accurate information, in the case discussed, the accessibility of quality variation of sheet metal materials. Accurate recording of properties along the length of the entire flat product, especially for coils, and open collaboration within the supply chain with this data has the potential to move from an experience-based to a knowledge-based approach and can unleash far-reaching optimization potential. Currently, there are numerous deficiencies that prevent the industry from tapping into this optimization potential.



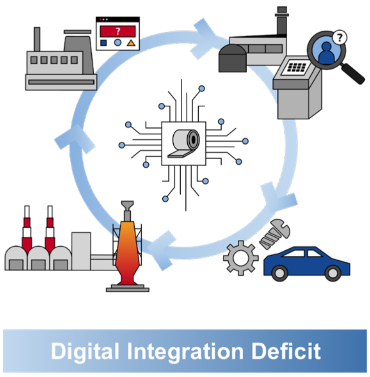
Methodological Deficit

Lack of methodology There are strict quality assessments for each coil supplied. Currently, mechanical properties are measured at the beginning and end of the coil. This does not capture the spatial distribution of the coil's mechanical properties. The use of non-destructive measurement techniques is not common, and if they are used, they are often only used for quality assessment rather than downstream process optimization.



Knowledge Deficit

Lack of knowledge The lack of information about the coil’s properties’ spatial distribution makes it difficult to react to occurring changes. As a result, companies rely on skilled workers and trial-and-error approaches to fix material related faults. Consequently, companies continue to rely on the experience of employees to parameterize processes when errors occur. This increases the risk of knowledge loss.



Lack of integration If only limited material data is exchanged within the supply chains, optimization potential along the supply chain can only be leveraged to a limited extent. Deeper digital integration for the sharing of data can enable the demand-specific production of steel products and establish feedback loops that lead to an overall optimization of steel products.

3.1 Methodological Deficit

Currently established material testing methods cannot provide the required information for the design of specific forming processes. For example, the tensile test is a common method for evaluating material quality, but its informative capability reaches its limits when complex stress conditions are considered. Due to the limited informative value of the test, material behavior under more complicated stress loads cannot be fully described and is therefore insufficient for the design of many steel processing operations. Even a multiaxial tensile test may be inadequate for complex processes because it covers only one property of the material out of many. In addition, such destructive material testing methods are inefficient in terms of material consumption [21], while the process of sampling can lead to uncertainties as material properties may vary depending on the sample tested [22].

At the same time, the steel flat product is not fully homogeneous and therefore, its properties may vary from start to end. Despite the strict tolerances used to ensure process stability and quality of sheet metal parts, fluctuations in material properties occur both within one and between multiple coils of the same batch [23]. These fluctuations can cause defects, such as burrs or sags in blanking processes, and springbacks in bending or forming operations [21]. Due to these variations in material properties, the sheet metal forming process experiences rejected components and operational challenges, such as downtime [24]. For an efficient use of resources, it is therefore necessary to enable a more comprehensive evaluation and quantification of mechanical material properties.

Sensor data recorded to determine material properties are currently already being used in initial approaches to optimize forming processes. In deep drawing, a flat metal plate is formed into a hollow cylindrical or conical body using a rigid tool and applying tensile and compressive forces. For this process, the tensile test represents realistic behavior of the material during the deep drawing process [25]. Heingärtner et al. used a multidimensional regression based on eddy current data to calculate material parameters such as tensile strength, yield strength, uniform elongation, and elongation at break during in-line production [26], the very parameters that can be determined from the tensile test. Fischer et al. presented a knowledge-based control approach for deep drawing that uses a so-called feedforward control based on material measurements from an eddy current sensor and a feedback control based on inline tensile tests to gain insight into material property variations in industrial processes [27]. Heingärtner et al. developed an intelligent control system that uses numerical simulations, material data from eddy current, process data, and tensile tests to optimize sink production [28]. However, considering the complexity of the forming processes, the information potential of these signals is currently not fully exploited, as they do not only correlate with the characteristic values obtained from the tensile test, but contain much more information about the structure of and stresses in the material [26].

Use case: Fine blanking is a sheet metal cutting process, which by its mode of operation is often classified as a forming process. Here, a punch and die are used to shear a metal strip or sheet, resulting in a blank with a flat edge and minimal flash. Fine blanking is a complex process that allows, but also requires, tighter tolerances and high precision (see Figure 3). This is because in fine blanking, the material is subjected to three-dimensional compressive stress in the deformation region near the blanking edge [29]. Due to the complex interactions, it is difficult to predict and control the result with the information given in current data sheets of coils. The industrial standard for evaluating the mechanical and technological properties of the coil is the uniaxial tensile test and the resulting quantities of yield strength and tensile strength [30]. However, the uniaxial tensile test does not represent the complex stress state during fine blanking. Since this information is critical, this fact prolongs ramp-up times for new incoming material and slows down the response to material-induced problems in production.

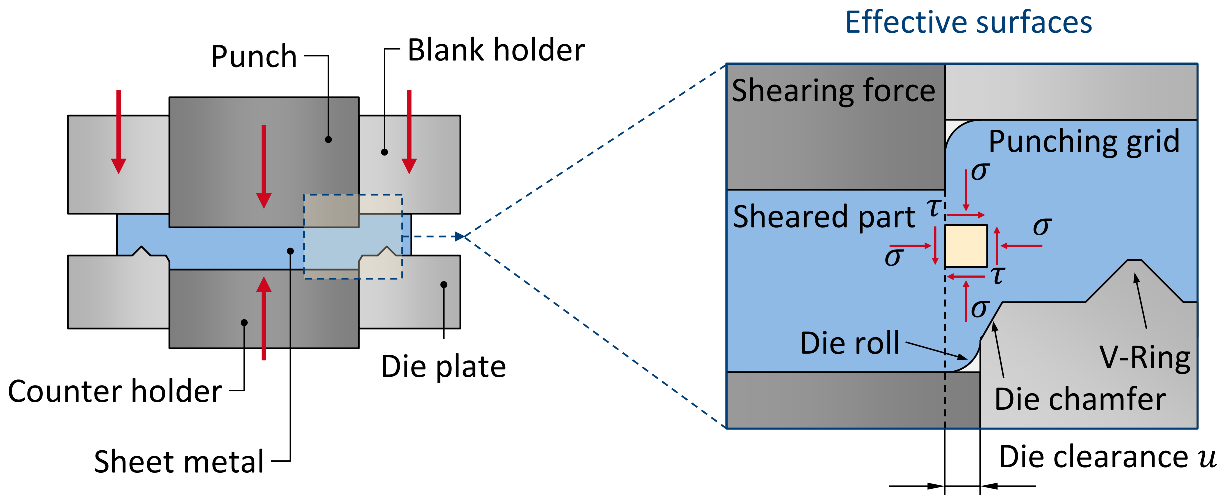


Figure 3: Effective surfaces of fine blanking process [31]

3.2 Knowledge Deficit

In contrast to tacit knowledge gained through experience, explicit knowledge enables easy transferability because the knowledge can be represented explicitly in the form of formulas, rules, and tables [32]. The reliance on tacit experiential knowledge in process optimization thus leaves companies vulnerable to 1. uncertainties caused by technological innovations in the supply chain, and 2. the loss of knowledge when key employees are no longer available, as the transferability of important know-how becomes more difficult, and the currently available explicit knowledge is often insufficient [33].

1. Tacit knowledge must be rebuilt when significant innovations lead to changes and, for example, new products and new materials differ too much in their properties from previous ones. This slows down ramp-up phases for the parameterization of processes. Since the changes presented in Chapter 2 can lead to a potentially large change in input materials, the ability of manufacturers to adapt effectively is even more important.
2. An overreliance on tacit knowledge in areas that affect the company's core business model increases the risk for companies to (temporarily) lose expertise due to employee failure, poaching, or retirement [34], resulting in a knowledge gap for the company.

The currently available data sheets do not provide explicit information of the material properties that are important for complex processes. Without the explicit information, building explicit knowledge is difficult, leading to reduced competitiveness [35]. Furthermore, the lack of availability of a holistic description of material data also hinders advanced collaboration between suppliers and processing companies, although intensive collaboration across company boundaries is a key factor for knowledge creation in manufacturing [36]. Due to the lack of explicit information about relevant material properties, communication about what is needed and which properties lead to problems in manufacturing is not possible, preventing specific requirements from being communicated to the supplier.

Use case: In fine blanking, the material undergoes a straightening process before being processed by the fine blanking tool. The parameterization of the straightening and fine blanking process is complex and currently based on implicit knowledge acquired through experience. Industrial practice shows that often and unpredictably, the processing of a new coil requires changes in parametrization to stabilize the process. To do so, predefined parameter sets for the straightening machine are used in a trial-and-error approach based on implicit knowledge. However, this often does not correspond to optimized settings in terms of productivity and sustainability. In cases where coils with the same material specifications and identical properties according to the data sheet behave differently in production, the need for higher data resolution and explicit information availability becomes apparent.

3.3 Digital Integration Deficit

Even if high resolution data of coils were currently already being collected, non-existent essential prerequisites for the successful digital integration of companies along the supply chains in sheet metal processing prevent their full utilization. In Germany, only 49% of companies are digitized and networked across companies, of which only 16% are networked with at least two cooperating companies [37]. The potential benefits of increased data sharing and data-based collaboration are often offset by inhibiting risks. While companies are generally interested in obtaining external data, the willingness of companies to share their own internal data with others is still low [38]. In a study by the Federation of German Industries (BDI), which surveyed 500 German-based companies about their current data usage and the biggest barriers to data sharing, only slightly more than 25% of companies were willing to share their product data and data from supplying companies [39]. However, current industrial examples of the digital integration deficit in the context of the metal processing industry are presented below.

The change in the automotive powertrain towards electric or hydrogen mobility requires adjustments and changes in the product portfolio as well as in the underlying requirements/tolerances [40]. This makes coordination with the supply chain important, since changes in quality tolerances, for example, have economic consequences and must be communicated or explored. Stricter tolerances at the supplier end, however, mean changes both in product and process design and in the selection of machines and raw materials. In addition, tighter tolerances result in higher costs due to inspections, special equipment, higher scrap or lower yields. Tooling costs can be significantly higher and machining times longer with stricter tolerances than with wider tolerances [41].

Not only do shape and position tolerances play a crucial role, but also sustainability requirements of contracting companies and governments require the exchange of information between companies within a supply chain. Due to the numerous possible influencing factors on the product to be balanced, e.g., material properties, waste, energy and water consumption, etc., large amounts of data are required from all parties involved in a supply chain. Only by digitally integrating the primary data it is possible to create a life cycle assessment of the highest quality. At this point, however, data sharing fails, among other things, due to the trust of the parties involved. Material data are often trade secrets and must be aggregated in a suitable form so that no conclusions can be drawn. But energy data must also be treated sensitively, as it can provide information about a company's utilization and efficiency.

However, there is a lack of infrastructure and the necessary framework conditions [42] that create trust [43] in data security and data sovereignty so that companies are willing to participate in data exchange and necessary requirements of today can be met.

4 Vision of Data-Driven Parameterization Based on Material Data

Approaches for cross-company use of materials data already exist, for example with the Material Digital platform [44], but the approach presented is more oriented towards benefit-oriented data exchange. In the following, approaches to the digital characterization of materials and intermediate results achieved so far are presented. Eventually, current initiatives for the digital integration of the supply chain to enable the vision presented in Figure 4 are discussed.

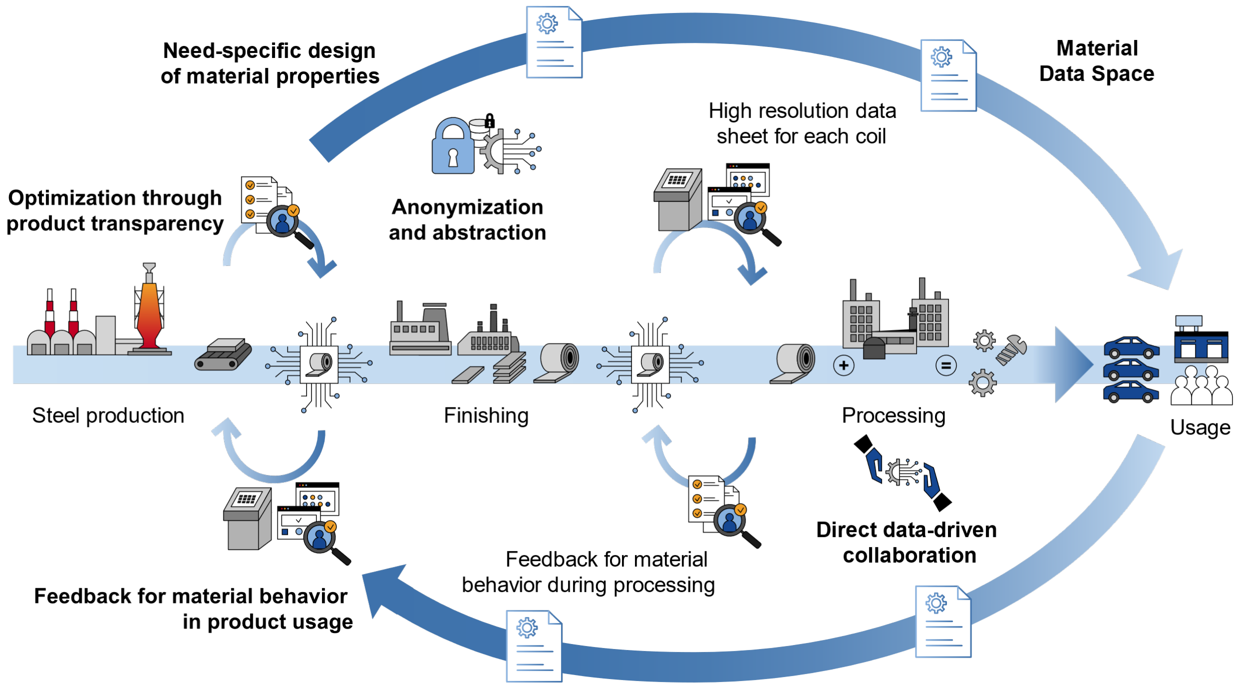


Figure 4: Optimizing supply chains through material data sharing

4.1 Upstream Process Data Driven Parametrization of Processes

As mentioned in Chapter 3.1, signals, for example from eddy current testing equipment, contain extensive information to describe material behavior, but interpretation and use of the data remains a challenge in obtaining relevant information.

Current limitations in understanding material data from complex sensing devices.

As an alternative to destructive testing methods such as tensile testing, non-destructive testing (NDT) is used to measure or monitor material properties along the coil without damaging the material. Engel et al. demonstrated the potential of NDT in sheet metal processing in 1994 [45]. Today, NDT allows direct determination of mechanical properties of materials, such as tensile strength or elongation at break, and can be performed regularly while the coil is being machined [26]. In addition to NDT, monitoring the process conditions of upstream processes such as hot and cold rolling can also provide indirect information on material properties during sheet forming [46]. However, research on the use of these data is still at the experimental stage and understanding of this complex and high-dimensional data is subject to significant limitations. For example, a single measurement with an eddy current testing system in the automotive industry provides a set of 48 data points in total [47]. Due to the possible nonlinear interactions between the individual data points and specific mechanical properties, direct correlation with the relevant physical quantities can be challenging. Another example of NDT is the magnetic Barkhausen noise measurement system, which is measured within a range of several MHz frequency sampling rates [48] and can detect residual stresses relevant to a variety of manufacturing processes in metalworking [49]. This signal has already been used in science to predict properties such as hardness over the entire length of the coil, using deep learning methods [50].

Reducing the complexity

The two examples above show that information is present in signals, but the complexity of the signals has so far aggravated direct inferences about mechanical properties in relevant application scenarios. One approach is to use pattern analysis to reveal the information in the data without directly relating it to mechanical properties. Methods that combine the information in an input data set into a lower dimensional set variables can provide an abstract perspective on the changing properties of the material. The hypothesis is that an abstract representation of the change in properties of the sheet will be good enough to provide subsequent process steps with sufficient reference values to tune their processes. Dimensionality reduction techniques vary in complexity from transparent and simple linear models to comprehensive nonlinear deep learning approaches. An example of a linear model is principal component analysis (PCA). It is considered a well-established statistical tool that reduces the dimensionality of large and complex data sets while preserving the most important information as measured by the variance of the entire data set. Thus, principal components capture the most significant variations in the data and can be used for visualization, clustering, and classification tasks [51]. That is, a low-dimensional representation of material properties such as residual stresses, microstructure, or tensile strength computed in this way provides a simple representation but is limited by the unspecified reference to physical quantities. Figure 5 visualizes the steps in a data-driven collaboration between sheet metal suppliers and processors to achieve effective process parameterization. Currently, only a small number of works exist that represent and visualize the varying material properties using the presented sensor technologies.

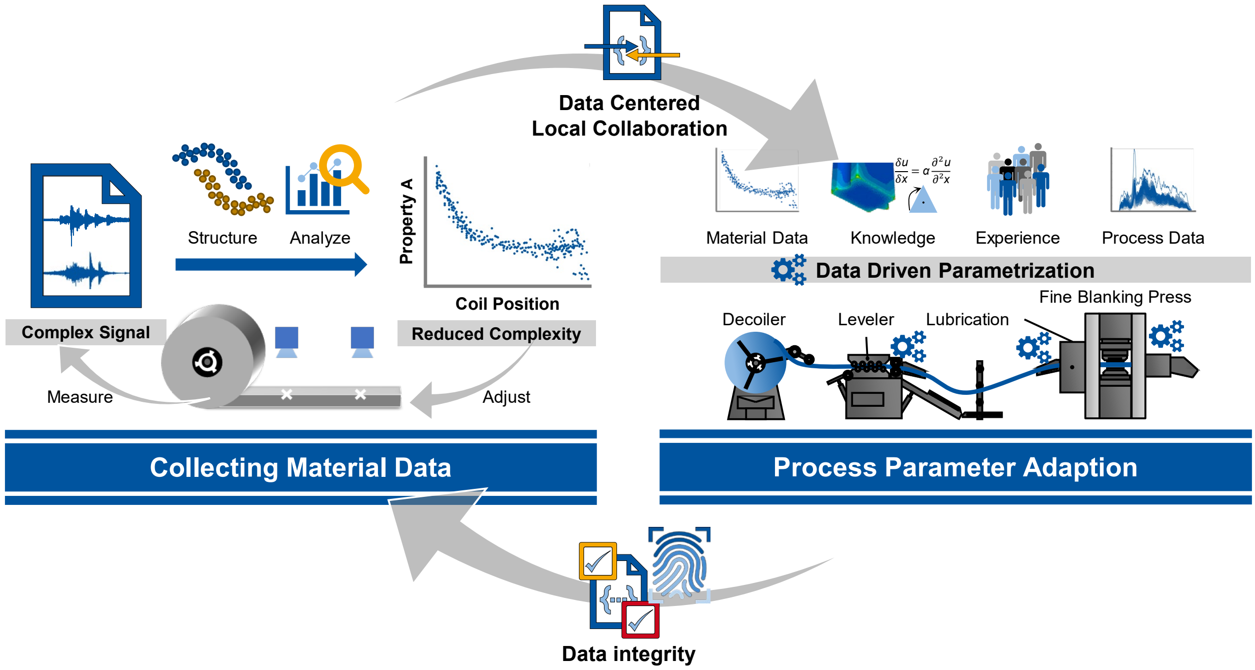


Figure 5: Data-driven collaboration between sheet metal supplier (left) and processor (right) for a data-driven process parametrization

Use case: Eddy current measurements and principal component analysis for monitoring the quality of cold-rolled carbon steel.

Cold rolling is a widely used process for producing steel sheets with high quality requirements, often used as an upstream process for fine blanking applications. The quality of cold rolled steel depends on several parameters, such as steel composition, temperature, thickness and rolling speed. Traditionally, the quality of cold-rolled steel is assessed by destructive testing of the final product. In experiments using an eddy current measurement system, measurements were taken after the cold rolling process at predefined intervals. Subsequently, the complex signal was transformed into a two-dimensional representation using PCA. It was shown that one of the resulting variables changes systematically in its distribution as a function of position in the length of the coil, indicating a strong correlation between the variables and the coil position. This distribution shows a nonlinear drift of the properties contained in the signals from the beginning to the end of the cold rolled sheet material. The result of the study was that, for the first time, the information visible in the PCA allowed the cold rolling company to gain detailed insight into its process results without destroying the final product for testing purposes. So far, however, it is not yet known how the information visible in the abstract representation can be directly linked to the mechanical properties.

4.2 Digital Collaboration

When developing a strategy for corporate data exchange, it is important to distinguish between (raw) data and information. Raw data has little value; it only acquires meaning when it is processed by a data analysis system and converted into information [52]. Using the information provided by material properties in Chapter 4.1, companies can adapt their manufacturing processes to increase efficiency [53]. Digital collaboration, e.g., by exchanging sufficiently precise material data between companies, can be summarized to two basic advantages:

From experience to knowledge

The use of process signals for the optimization and control of manufacturing processes is an established approach [54], whereby the (input) material or knowledge about the material can be attributed a special potential since its nature has a significant influence on the process and the resulting quality [55]. However, a metal processing company is not interested in the complex original output signals, nor necessarily in the actual spatially resolved mechanical property data of the material being processed. Rather, what is decisive is a set of information which can be used as a reference value together with the knowledge within the company to adjust the process parameterization. By exchanging and using such anonymized information, which only contains an abstracted value, a limited transparency is maintained in favor of the material supplier and at the same time the possibility is created to use this orientation variable as a reference for feedback on the material behavior in use. This can be described as a benefit-oriented exchange and collaboration based on data.

Added value through collaboration

By using abstract values that enable selective information sharing, supplying companies can ensure that their customers receive only the information they need to adjust their manufacturing processes without completely compromising the confidentiality of their own production quality. Within an iterative collaboration process, material suppliers and processors can now work together to understand how materials behave in often long-running product groups, so that over time the sweet spot in the adjustment of material properties with optimal usage behaviour in manufacturing, in relation to the target variable, can be determined. In cases where there is a high degree of trust between the parties, this collaborative approach can thus enable suppliers to both provide their customers with the information most relevant to the use case and better tailor their products to the customer's specific needs.

The following use case presents initial findings that could serve as a basis for data-driven optimization in industry.

Use case: Process chain cold rolling – fine blanking

The study discussed below is a continuation of the use case presented in Chapter 4.1 as part of the SPAICER research project (FKZ 01MK20015A). The objective of the study was to identify the dependencies between the parameterization of the straightening equipment, the provided data of the cold rolled material and a quality measure of the resulting components. A non-destructive testing system based on eddy current was used to measure the cold-rolled steel. The results showed that linear models can be used to reveal a significant relationship between the parameterization of the leveller, the material data provided, and a quality measure of the resulting components. This finding suggests that a targeted parameterization of the straightening process based on available material data is possible. However, further experimentation is needed to quantify the potential more accurately and substantiate the results. The results of this study justify the significance of collaboration between the cold rolled steel supplying company and the fine blanking company to gain understanding of the relationship between cold rolling and fine blanking. However, to reap the full benefits of this collaboration, it must be accompanied by digital integration throughout the supply chain.

4.3 Digital Integration of Supply Chains

The use case presented in chapter 4.2 shows that direct collaboration through increased data exchange between supplying and processing companies of sheet metal can bring deeper understanding. However, applying the concept to data sharing across the supply chain presents greater challenges in organizing, sharing, and protecting data. In a local collaboration, for example between material suppliers and processors, data is shared between two direct parties with an agreement and already established trust. The (automatic) sharing of data in a group of companies complicates the situation considerably. Data sharing initiatives already exist that define the framework for expanding the digital integration of companies in a supply chain. The basis of any initiatives and standards for data exchange in collaborative networks such as a supply chain are the International Data Spaces Association e.V. (IDSA) and Gaia-X (see Figure 6), which are therefore considered fundamental and are briefly described below:

The IDSA is an industry-driven foundation founded in 2016 to create a secure data space for the sovereign management of data assets in companies across various industries [56]. The IDSA currently has more than 130 participants from 20 countries. The Gaia-X Association is also working on a concept for data-driven ecosystems. It was founded in 2021 and currently has 355 participants [57]. The connection between Gaia-X and IDSA is based on a common desire for data sovereignty and a trust-based ecosystem for data sharing. In this regard, Gaia-X's infrastructure is predominantly based on IDSA's infrastructure. In contrast to IDSA, Gaia-X introduces concepts that address data storage and related elements of the cloud. Gaia-X focuses on sovereign cloud services and cloud infrastructure, while IDSA focuses on data and its sovereignty. The underlying trust models are also different. IDSA focuses on gateways for edge and cloud applications. Gaia-X, on the other hand, on identity and trust methods that support security levels, state tracking and certification applications.

Based on the two initiatives presented, the so-called Collaboration Spaces, Manufacturing-X, Catena-X, and Mobility-Data-Space initiatives were created [58]. While Catena-X specifically looks at the automotive supply chain, Manufacturing-X tries to achieve similar results for different industrial sectors. Both initiatives are Gaia-X compliant IDSA systems and operate as open collaborative ecosystems providing standards, applications, services, and transfer. The Mobility Data Space is an applied ecosystem based on a Gaia-X compliant IDSA system for the German mobility sector.

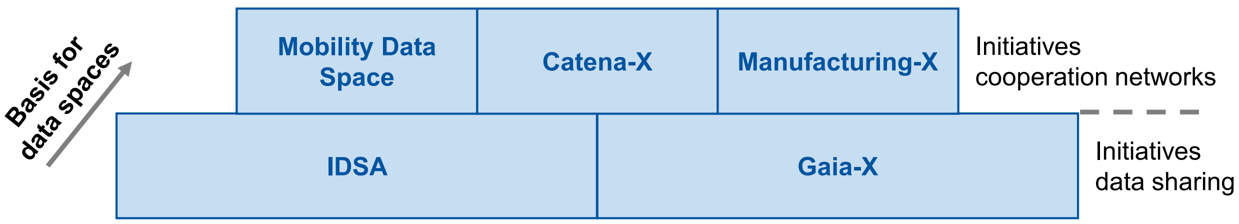


Figure 6: Initiatives for data spaces

In the initiatives, the specific concerns and risk factors of data sharing are addressed and worked on within the consortia. These risks include defining technical factors such as structure, format, types, and content of data, as well as selecting appropriate communication protocols. Currently, data sharing is hindered by the lack of a legal framework [59], interoperability, and the many individual stand-alone solutions rather than the use of universal standards [60], resulting in higher costs when implementing a data exchange [61]. If no standards exist for the storage and structuring of data, there is also the uncertainty of incompatible data sets [42].

5 Quantification of Sustainability Impact?

The vision of the comprehensive use of material data along the sheet metal supply chain sheds light on the potential that lies behind an implementation of NDT technology. The current results of the described use cases in chapters 4.1 and 4.2 show the potential of using NDT measurements for transparency of material properties and process optimization. This illustrates that with the adoption of this technology and an increased focus on collaboration, sustainability and cost efficiency can be improved. However, why are stakeholders hesitant to implement this technology, even if they are convinced of the vision? The following reasons can be given:

1. **Trust** Direct partnerships with long-term relationships foster high levels of trust, making data sharing a feasible and realistic practice. Data sharing along the supply chain can have a high impact, but often seems impossible for SMEs in the automotive supply chain. Many companies have reservations, based on experience, that increased transparency at any scale will enable customers to negotiate better prices. However, for large-scale data sharing to deliver benefits, companies must be willing to share their data, even if they do not directly derive benefits.
2. **Resources** The introduction and development of innovative solutions to increase sustainability and cost efficiency increasingly require collaboration across traditional fields of expertise. The specialization of SMEs is thus faced with an increased need for interdisciplinary expertise, making collaboration with external knowledge providers, such as universities, a key task. For example, the introduction of digital technologies requires innovative hardware, digital infrastructure, and data expertise to develop digital services. A sheet metal processing company that specializes in manufacturing components for automotive applications with complex geometries often lacks the necessary skills to develop digital solutions, manage technical IT cloud infrastructure, and analyze material and process data. In addition, SMEs avoid working with IT companies to develop such services because the services are tangential to the core of their business model or involve high costs as well as major risks.
3. **Costs** The risk associated with the introduction of such a technology is high, while the current situation of the industry is in many respects anything, but secure and free capital is not available. Measures to reduce financial risk and encourage collaboration are publicly funded research projects in which large consortia allow companies to leverage the expertise of universities and companies in other fields. Large projects with sufficient funding to develop such solutions often involve a significant number of non-value adding overhead. These consist of numerous meetings for communication and coordination, accounting details, and additional workload. While this overhead is manageable and may be justified in terms of funding guidelines, for a mid-sized manufacturing company, the additional capacity often cannot be readily compensated for by existing personnel with project management experience. From an SME's perspective, participation in a publicly funded project

can provide a competitive advantage, but it always involves a trade-off that must be considered when planning new projects and maintaining day-to-day operations. And while the amount of money that companies can provide as part of such projects is reasonable, it is small compared to the substantial funding provided for projects such as Catena-X [62] or the government-supported shift to hydrogen-based steel production [63].

The quantification dogma in sustainability

Currently, the question of quantifying sustainability impact of technologies is increasingly important when evaluating measures that contribute to a green economy. As this article shows, the introduction of NDT-based continuous material measurement for all cold-rolled coils as a single measure enables far-reaching optimization potentials in terms of energy use and scrap avoidance. However, the real potential of hitherto unknown magnitude lies in improved cooperation between direct partners and the entire supply chain. This potential is offered by the improvement of coil quality as well as the parameterization of coil processing, which in turn can reduce scrap to a minimum during parameterization. In addition, the transition from 100 years of tacit or silent experiential knowledge to explicit knowledge that can be easily communicated through language or implemented in digital services is potentially enabled by the introduction of the discussed system. Since the actual potential does not result directly from the one measure, but from a series of measures and paradigm shifts to be implemented simultaneously, quantifying the impact to a single SDG, such as CO_2 impact using sophisticated Life Cycle Sustainability Assessment methods, is extremely complex and difficult to assess for SMEs. Currently, the emphasis is primarily on contemplating the reduction of carbon emissions, while other goals and targets for a sustainable world are even more challenging to consider and assess.

At the same time, companies cannot be expected to act exclusively in the interests of sustainability when a significant part of the status quo in the industry is currently undergoing disruptive change in the short or medium term. This development is impacting existing business models as, for example, the components required for the various future powertrains are changing, with parallel changes in supply chain inputs due to innovations in steel production. While this paper describes necessary actions with their impacts, the business decision to "just do it" cannot be based on quantifying sustainability impact, nor can it be based on estimated monetary impact, as the work required to assess these impacts exceeds the capacity available to make this decision. Instead, innovation decisions must and will be made by the intuition of smaller and larger companies in situations of high uncertainty and risk, taking into account their personal responsibility for the sustainability of production and the economy as a whole. This key factor or skill has been crucial in the history of German industry and will also be required to meet the challenges of green change.

6 Literature

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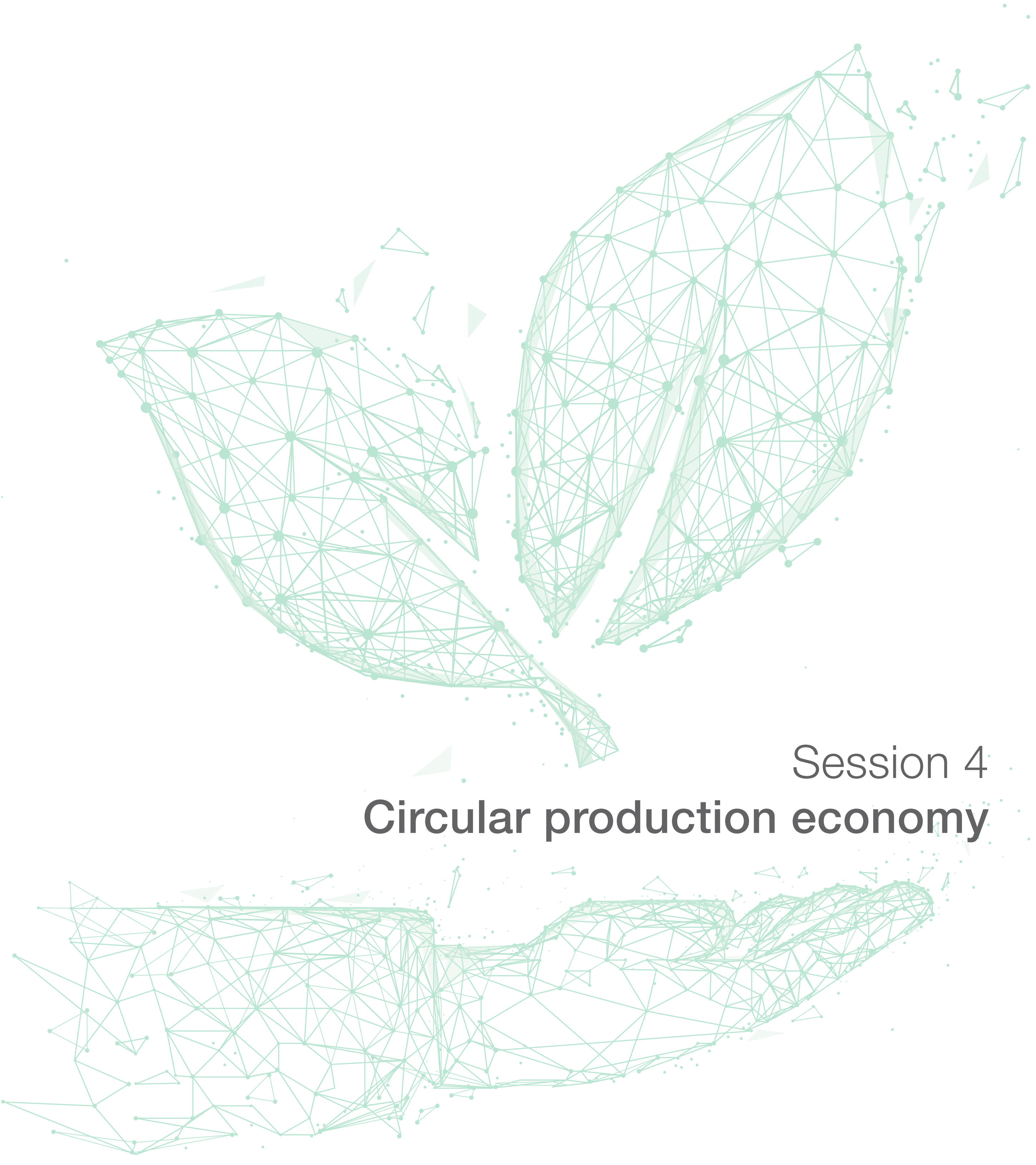

Session 4

Circular production economy

4.1 Framework for Circular Production Economy

G. Schuh, S. Schmitz, G. Lukas, L. Niwar, M. Welsing, R. Calchera

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Abstract

Framework for Circular Production Economy

The value-enhancing circular economy is a concept for the sustainable production of Goods. A central aspect of the value-enhancing circular economy is the reduction of the ecological footprint. At the same time, successful implementation of the concept supports accomplishing of targets in the dimensions of economic efficiency and innovation. A consistently aligned value-enhancing circular economy eliminates the ecologically negative consequences of production and increases the long-term value creation and profitability of the companies involved. This paper motivates and explains the concept of the value-enhancing circular economy. In addition, a framework is presented that supports companies in the transformation process towards it. For this purpose, the product architecture, the business model as well as the innovation and value creation strategy are detached from the paradigms of the established linear economy and oriented towards value enhancement and longevity. In order to ensure that all stakeholders have access to the information required for their participation, the digital shadow in the Internet of Sustainable Production is necessary. For the extended product life cycle, a digital product file acts as a digital shadow, bundling and aggregating all relevant information.

Keywords: Value-enhancing Circular Economy, Production, Upgrade, Framework

Kurzfassung

Ordnungsrahmen für eine zirkuläre Produktionswirtschaft

Die wertsteigernde Kreislaufwirtschaft ist ein nachhaltiges Konzept für die Produktion von Waren. Ein zentraler Aspekt der wertsteigernden Kreislaufwirtschaft ist die Reduzierung des ökologischen Fußabdrucks. Gleichzeitig ermöglicht die erfolgreiche Umsetzung des Konzepts auch eine Zielerfüllung in den Dimensionen der Wirtschaftlichkeit und Innovation. Eine konsequent ausgerichtete wertsteigernde Kreislaufwirtschaft eliminiert die ökologisch negativen Konsequenzen der Produktion und erhöht die Wertschöpfung und Profitabilität der beteiligten Unternehmen langfristig. Der vorliegende Beitrag motiviert und erklärt das Konzept der wertsteigernden Kreislaufwirtschaft. Zudem wird ein Framework präsentiert, welches Unternehmen bei der Transformation unterstützt. Dafür werden sowohl die Produktarchitektur, das Geschäftsmodell sowie die Innovations- und Wertschöpfungsstrategie von den Paradigmen der etablierten, linearen Wirtschaft gelöst und auf eine Wertsteigerung und Langlebigkeit ausgerichtet. Damit alle Stakeholder die zur Partizipation notwendigen Informationen abrufen können, wird der digitale Schatten im Internet of Sustainable Production als Basis für die Realisierung miteingebunden. Für den verlängerten Produktlebenszyklus fungiert zudem eine digitale Produktakte als digitaler Schatten, in dem alle relevanten Informationen gebündelt und aggregiert werden.

Schlagwörter: Wertsteigernde Kreislaufwirtschaft, Produktion, Upgrade, Framework

1 Introduction

Climate change, biodiversity loss and increased global pollution pose significant challenges to society. They affect the ecological balance of the Earth, risking the livelihoods of current and future inhabitants [1]. These challenges jeopardize the opportunities of future generations; therefore, it is imperative that durable solutions to these threats be found quickly.

Production plays a central role in addressing climate change due to the effects associated with production such as resource consumption, waste volumes, environmental pollution and greenhouse gas emissions. Gases such as carbon dioxide, methane and chlorofluorocarbons have a direct impact on the global greenhouse effect. Greenhouse gas emissions are a political focus, as they directly contribute to the Earth's temperature rise. To meet the 1.5°C target of the Paris Climate Agreement, global CO_2 emissions must be reduced as a contributor to climate change [2]. The energy requirements of manufacturing and logistics alone account for over 40% of worldwide CO_2 emissions [3]. A reduction of greenhouse gases in production processes and transportation is thus not only desirable, but also indispensable. Greenhouse gas emissions are not the only negative impacts generated in the manufacturing sector. Increasing consumption of limited resources inevitably leads to scarcity. Therefore, manufacturing companies face the question of how to deal with the increasing scarcity of resources.

One of the challenges for companies manufacturing and marketing sustainable products is that many customers are interested in environmentally friendly or ethically produced products but are not willing to pay a higher price for them. Although many consumers have increased awareness of environmental issues and have an interest in sustainable products, for many, price is a key criterion in the purchasing decision, [4] to overcome this challenge, companies need to find ways to reduce production costs for sustainable products and change customer perceptions about the importance of sustainability. As a result, cost savings are often a primary motivation for taking action to improve sustainability rather than an actual desire to be more environmentally friendly [5]. In the meantime, however, the question arises as to what extent a traditional production model is still profitable in the long term. Energy and input material prices have risen due to global political and security events but cannot be passed on directly to customers due to contractual obligations, competitive pressures and/or customers' low willingness to pay these price deltas. In 2022, manufacturing industries passed on only 50% of their increased costs [6]. If companies lack the means to cover the costs they have incurred, this jeopardizes their business basis. Price increases due to short-term turbulence are a preview of the long-term situation for companies. Prices will continue to rise due to limited availability of raw materials [7]. Therefore, the manufacturing industry needs new solutions to keep existing resources in cycles and thus reduce the threats to the environment and society caused by waste generation.

Current measures taken to achieve sustainable production have indeed helped to reduce the environmental footprint of production. However, measures with savings in the single-digit percentage range are not sufficient to achieve truly sustainable production without a harmful impact on the environment. Much more significant savings or even completely new approaches are needed. For example, a company can reduce its CO_2 emissions by using renewable energy and energy efficiency measures. Most companies look at production processes independently instead of considering the entire life cycle of a product. As a result, the environmental impact of a product in individual phases is not fully captured and the actual impact is underestimated.

A comprehensively sustainable approach requires a holistic view of the entire life cycle of a product, from raw material extraction to production, transport, use and reuse. Companies need to focus on minimizing their environmental impacts at all stages of the life cycle, while taking into account the social and economic impacts of their production [8]. When a company tries to achieve too high economies of scale and, as a result, produces too much, it has significant environmental impacts. The impacts affect the climate, air and water quality, and biodiversity. It is important that companies make their production processes sustainable and ensure that they only produce as much as is actually needed to minimize environmental impact. One approach to producing fewer new products is to extend the life of products. To ensure that consumers do not have to forego technical innovations in the process, this approach requires an option for upgrades. Upgrades are used to introduce new functions into a product. These new functions also lead to an increase in the value of the updated product and offer companies the opportunity to generate sales independently of new production. Such an approach is also referred to as value-enhancing circular economy and is explained and motivated in more detail in the following article.

Current approaches promise the reduction of greenhouse gases, lower energy consumption, improved recycling facilities and resource-saving products. These approaches address individual problems but do not encompass a holistic approach. It is necessary to identify an approach that aligns the production economy in a manner that encourages the cessation of climate change, the preservation or restoration of ecosystems, and the well-being of all living beings on our planet. A value-based circular economy promises to solve current problems in the production context, and to balance economic growth with resource scarcity. As a holistic system, the value-enhancing circular economy considers the entire life cycle of resources and sustains them within the system. The idea of economic development towards a holistic circular economy also manifests itself politically. In the European Green Deal of 2020, an action plan including concrete measures to develop the economy towards a circular economy is firmly established [9]. Political pressure on companies to change their production processes is increasing, as is social awareness of sustainable products [10]. This offers a significant opportunity for the development of new technologies and the active promotion of new business models.

If one examines the concept of a value-enhancing circular economy, intuitively there are predominantly positive aspects. Therefore, the question arises why many manufacturing companies are still far away from a transformation and stick to existing linear economic systems. A closer look at the components of a value-enhancing circular economy provides insights into the current obstacles for companies. Establishing a value-enhancing circular economy requires the development of new products, the manufacturing of those products, and an acceptance for this products. Established product development leads to complete solutions with new features that encourage the disposal of obsolete products, removing them from circulation. Instead of encouraging the move towards a value-enhancing circular economy, this only leads to even higher volumes of waste and further dependence on limited resources. Existing technical consumer goods are highly integrated products that are difficult to repair due to increasing complexity and require high recycling efforts. A shift towards modular products, characterized by easy replacement of components, offers increased repairability and expandability. However, this complete reorientation of products requires a restructuring of production processes. Currently, transition costs, such as investments in technological projects, training of employees for new activities, as well as production retooling, prevent companies from restructuring their production to sustainable product capabilities [11]-[12]. Even if the financial resources were potentially available to establish new production, companies often lack the in-depth expertise and technological knowledge to implement it [14], [15].

Production processes have been optimized in many companies for a long time. The industrialization of remanufacturing and upgrade processes requires a comprehensive revision of production planning, process optimization, organization and IT systems to enable efficient and scalable production of remanufactured products. To achieve this, it is necessary to consider functional enhancements, i.e. upgrades, in the re-production process. Re-assembly upgrade processes save up to 90% of the material and environmental impact of new products and increase the value added per employee, e.g. in vehicle production, by about 30-60%. It is important to make an accurate forecast of demand for remanufactured products and to ensure that enough used products are available to meet production needs. The organization must be adapted to enable smooth and efficient production of remanufactured products. This includes training employees on the specific requirements of the upgrade process. Quality assurance is also critical to industrialized remanufacturing. It is important to ensure that remanufactured products meet the same standards as newly produced products. If both new product development and production process restructuring are possible, customer requirements are the next barrier to establishing a value-enhancing circular economy. Customer demands for products to be as affordable as possible, to meet new design requirements, and to reflect current trends do not always align with the use of remanufactured and durable products utilizing recycled materials.

If the aforementioned challenges of a value-enhancing circular economy are mastered, the system offers diverse potentials for the participating companies. For example, with fewer factories, a double-digit percentage increase in sales is achieved, with a simultaneous reduction in greenhouse gas emissions. In addition, the margins of manufacturing companies in particular are doubled. The reason for this is the aforementioned expansion of functions and increase in value, which enables a constant consumer demand with lower production and resource expenditures.

2 Value-Enhancing Circular Economy

Efforts for sustainable production and environmentally friendly processes have existed for as long as the associated understanding of the problem. For this reason, diverse approaches are already associated with the terms sustainable production. However, since these approaches have not achieved the desired effects of an environmentally neutral or even positive balance, the understanding of sustainable production must be expanded. Sustainable production is achieved through new approaches, such as value-enhancing circular economy, which do not exclude but complement existing measures (see Figure 1). By rethinking and introducing a value-enhancing circular economy, the opportunity arises to establish sustainable production not only for reasons of the previously lacking sustainability, but also because of its profitability. This is because, in the long term, consistently implemented sustainable production offers the greatest potential not only for the environment, but also for profitability and innovation, especially if the principles of the value-enhancing circular economy are taken into account.

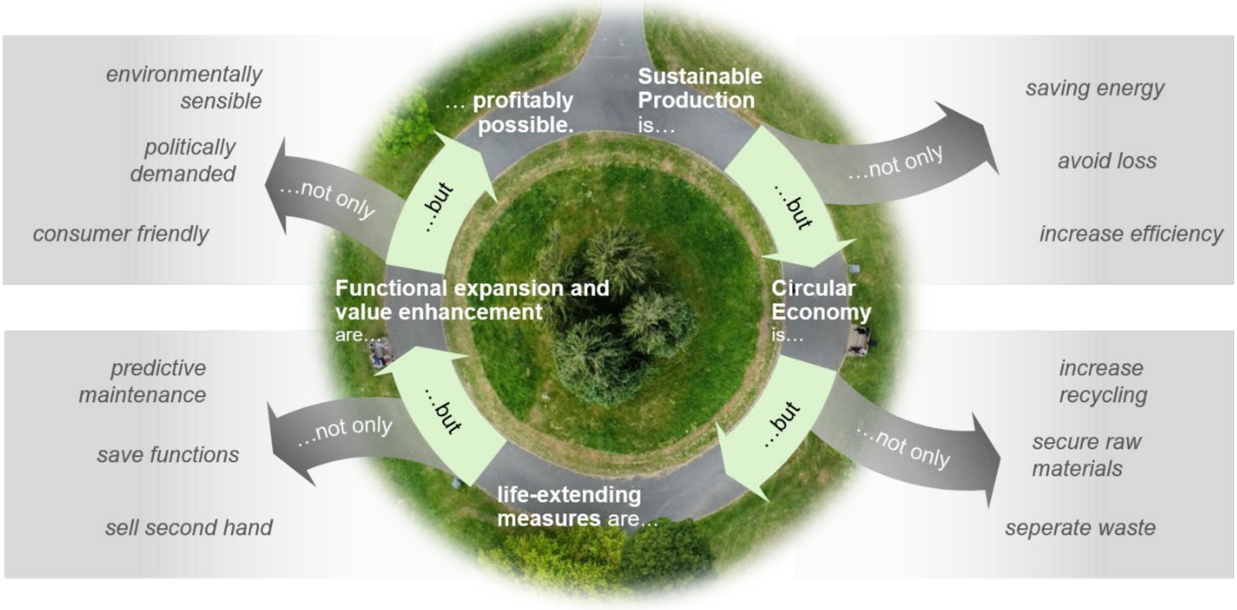

Figure 1: Contribution of value-enhancing circular economy to sustainable production

The existing approaches within the linear production understanding with regard to sustainable production are characterized by energy saving measures, scrap reduction and efficiency increase. These approaches initially appear ecologically motivated, but also have a financial drive. In particular, rising costs for energy represent a motivation for saving measures. Increasing efficiency and reducing scrap within production provide both less impact on the environment and cost savings for the company [16]. However, simply increasing efficiency and optimizing energy consumption are not enough to transform production into neutral or environmentally positive processes. Production that is optimized in its efficiency still requires new resources to produce products. To eliminate resource consumption, a system is needed that not only increases efficiency, but also builds a circular economy by reusing existing products. This requires a shift in thinking by companies and differs from the traditional understanding of production, where new resources are used to make products, which are later disposed of after their useful life. With consistent cycles, it will be possible to implement environmentally neutral processes and achieve long-term environmentally positive effects.

In the long term, the entire production economy must be rethought and a circular production system established. The current understanding of a circular economy consists mainly of concepts such as recycling, waste separation, and securing raw materials. Products are not disposed of properly or, with regard to unused cell phones, remain in drawers. End customers thus represent a significant hurdle in the implementation of recycling processes. Recycling the individual components of a product also requires significantly more energy than continuing to use a product. While companies intuitively develop products that will need to be replaced in the near future, in the end, it is more sustainable for both the company and the environment to produce products with a longer lifespan. Extending the life of a product generates less resource use and waste, which helps reduce environmental impact. At the same time, companies gain economic benefits by implementing life extension measures. Developing products with a long life span not only reduces the need for recycling, but also reduces the need for new products. Which would in turn reduce the production of new goods, lowering the energy and raw materials requirements. Customers appreciate it when a company offers life-extending measures. A longer product life leads to higher customer satisfaction and customer loyalty. In addition, companies that engage in life-extending measures strengthen their image as a sustainable company. In the end, this helps to gain customer trust and create a positive perception among other stakeholders [17].

A durable product that is resold after its use instead of being disposed often reduces the consumption of limited and environmentally harmful raw materials. The number of suppliers who buy back old equipment, refurbish it, and sell it for a lower price has increased due to the change in demand [18]. Other companies specialize in the remanufacturing of end-of-life devices. For this purpose, various end-of-life devices are purchased from end users, refurbished and resold. One example is the market for mobile devices. Changing a smartphone battery is often enough to maintain the original function or even extend the original battery life, thereby allowing the device to be resold and used again. One challenge for companies is that the return of products is not be precisely predicted. In addition, the rate of development of new devices is so high that remanufacturing must be done more quickly to bring remanufactured devices to market quickly and offer attractive deals [19]. In addition, this type of remanufacturing is not fully competitive due to the lack of function enhancement and therefore some customer groups prefer new products. Life-extending measures are also used in manufacturing to keep machines and equipment running with as little downtime as possible. For this purpose, usage data are analyzed so that the behavior of the machines is predictable [20]. While this predicts failures in production better and extend the life of machines, it cannot achieve completely sustainable production because this measure focuses only on the life of machines. By extending the life of machines, resource consumption and waste production are reduced. Thus, these are essential measures for the sustainable development of the industry. However, if the products become more durable, there is a lack of market demand and thus a demand for new technologies. The continuously increasing scientific and technical development could thus slow down or stagnate. This is a challenge for society because new technologies offer a variety of benefits. Technological development helps to make processes more efficient and to create solutions for our current climate impacts. A society changes over time, but stagnant economic development does not offer companies a chance to respond to new needs with appropriate solutions. Therefore, companies need ways to increase the lifetime of products without hindering technical development. To ensure continued usage of old products, one possibility is to upgrade and extend functionality though updates and upgrades rather than purely relying on increased maintenance [21]. Although intuitively life-extending measures are not associated with either technological progress or product upgrading, function enhancement creates a competitiveness of remanufactured products relative to new products. Upgrading products in the context of the value-enhancing circular economy is therefore referred to as upgrading circular economy. Such upgrades are made possible by new product modularity. This enables companies to improve the performance of their products and thus increase their value [22]. The updatability of a product has a positive long-term impact on the environment without inhibiting the innovative power of companies [23]. The new product modularity and the possibility to continuously improve the technological value promotes the social development and the long-term maintenance of a value-enhancing circular economy [24]. From the already established concepts of modularity, new product modularity differs in its orientation. In contrast to traditional product modularity, where each module is usually responsible for a specific function or feature of the product, new product modularity refers to a modular structure that allows for greater flexibility and adaptability. This makes it easier to replace wear parts, integrate new functionalities more quickly, and maintain standard features. New product modularity enables companies to respond quickly to changing market conditions or customer needs by using modular designs that allow them to easily change or customize the product by adding, removing or replacing specific modules. This allows companies to bring their products to market faster and more cost-effectively while meeting a wider range of customer needs.

The possibility of keeping products on the market for a long time based on function extensions and value increases is ecologically sensible due to the resource-saving nature [25]. Life-extending measures are therefore also demanded at the political level. In early 2022, as part of the goal to make Europe the first climate-neutral continent by 2050, a proposal was presented by the European Commission to revise consumer protection regulations. This stipulates that companies must provide information on the lifespan of their products and provide details on the reparability of their products. Furthermore, lack of information about features that specifically limit the lifespan would be considered an unfair business practice [26]. Consumers benefit from the resulting low-cost opportunities to integrate new technologies into their existing devices. By adhering to the principle of new product modularity, emphasizing the technical core functions of the product, and incorporating interchangeable function extensions, it is possible to reduce the production effort required. This enables companies to make the improved product available to consumers at a lower cost compared to a completely new product. Broader coverage of different market segments through a low-cost basic variation or variations with the latest technology and full range of functions meet more customer requirements. A modular product policy makes sense for both the environment and society in terms of policy requirements and customer satisfaction, but is associated with reduced competitiveness. Yet new product modularity make financial sense for companies. By covering a wider range of market segments, greater market coverage is achieved and more revenue generated for the company. For the company, the new product modularity additionally offers high customer loyalty, as customers want to upgrade their products in the long term. Switching to another manufacturer involves a higher financial hurdle, as the basic framework of the product would have to be purchased anew instead of merely acquiring the functional expansion. Long-term customer loyalty thus offers the opportunity for predictable and constant revenue, which achieves higher profit margins. This is possible if the new purchase by customers is substituted by an upgrade. An upgrade offers the customer a similar added value as a new product, which is why there is a similar willingness to pay. At the same time, however, an upgrade means significantly lower expenses for a company and thus a greater difference between costs and market price. These savings thus lead to increased profitability while simultaneously reducing the burden on the environment and resources.

Overall, in terms of sustainable production, it is necessary to challenge intuitive thinking and consider innovative approaches such as the value-enhancing circular economy and new product modularity. Production that is circular in nature, implements life-extending measures at all levels, and enables value retention by taking products back for repair or functional extension makes sense in all dimensions of sustainability. Moving from traditional linear production to sustainable, closed-loop, circular production requires structural changes in a company. The way production processes are run, products are developed and how stakeholders are dealt with changes. A framework for implementing such an Upgrade Circular Production Economy will enable companies to implement a value-enhancing circular economy.

3 Framework for Circular Production Economy

To achieve a Circular Production Economy, a manufacturing company must break down dichotomies that affect all areas of corporate strategy. The diagram in Figure 2 shows the resulting fields of action in the framework for Circular Production Economy and offers the possibility of positioning a company. For this purpose, the company's competitive strategy is marked in the four quadrants on the respective axes. For a consistent strategy fit of the competitive strategy, manufacturing companies have to make their strategy positions similar in all four quadrants, i.e. place all positions either in the center or at the edge of the framework. A deviation results in a mis-fit, which inevitably creates competitive disadvantages [27].

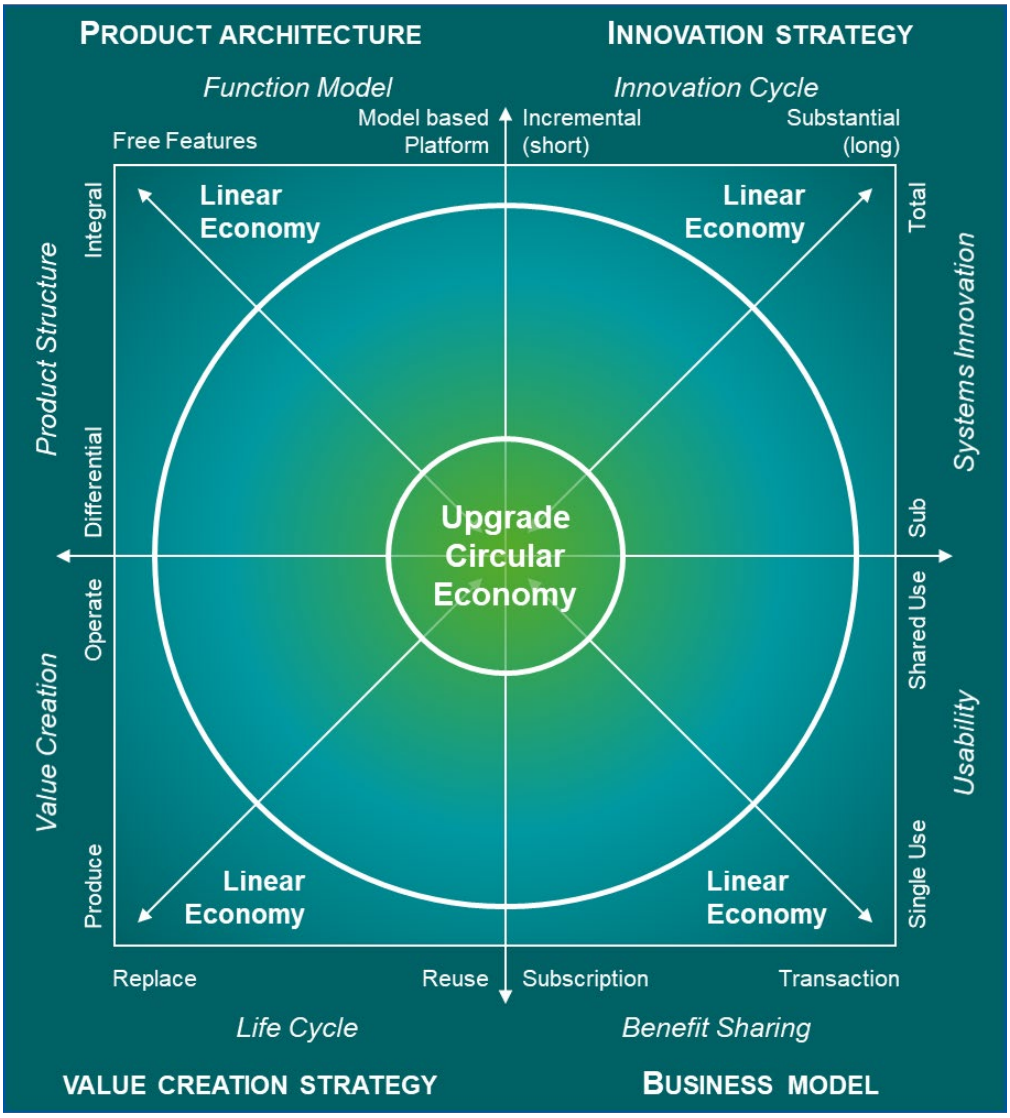

Figure 2: Framework for Circular Production Economy

A positioning in the middle of the diagram shows that the corporate strategy is in line with the principles of Upgrade Circular Production. A company positioned in this way can establish a value-enhancing circular economy with comparatively little effort. The outer ring of the framework represents the characteristics of the classical, linear economy. Companies that occupy the edge in all aspects of the strategy also have a consistent and consequential strategy. However, this strategy is not in line with the strategies mentioned in chapter 1. A critical examination is therefore recommended, particularly with regard to future regulations and customer requirements. For companies that do not create a consistent image in their positioning, the framework offers assistance. It recognizes in which areas the company is already well positioned and in which areas there is a need for action. In addition, the exact positioning on the axes reveals how urgent the respective need for action is. As soon as a company decides to focus its activities more strongly on the circular economy upgrade, the framework can also be used to monitor the status of the transformation.

Product architecture is the first quadrant of the Circular Production Economy framework. A product architecture describes the structure of a product, including the arrangement and functions of its components. It is used to facilitate the development, production and maintenance of the product and to ensure that it meets customer requirements. Therefore, the product architecture is divided into the Product Structure and the Function Model of the product. For the product structure, a distinction exists between differential and integral design. Differential construction refers to a design in which different components or systems are developed separately and then assembled. Integral construction, on the other hand, refers to a design in which different components are so closely linked that they form a single unit and are developed together. The difference is that integral design seeks greater integration and collaboration among the various components or systems, whereas differential design focuses on the separation and specialization of components. Thus, differential design facilitates the new modularization, i.e., the separation of functions in individual modules [28]. The functional model considers the individual functions that a product should realize with respect to customer requirements. For the framework, a distinction exists between free features and model-based platforms. Free features are specifically adapted to customer requirements independently of standards. Model-based platforms, on the other hand, create a framework including specifications for the use of features in a product. In conjunction with a differential design, functions are thus added via modules, for example, in order to achieve a functional extension.

The innovation strategy is mapped via the Innovation Cycle and Systems Innovation axes. The Innovation Cycle describes the speed of innovation, which is determined by market requirements and technology maturity. Products with a high level of technological maturity and constant market requirements are generally improved incrementally. In other words, innovations are introduced to the market at short intervals, step by step and building on each other. These innovations correspond to a continuous improvement in the product. The opposite of this is substantial innovation. This type of innovation cycle involves the release of completely new functionalities and product features that aim to have a disruptive effect on the market. Due to the basic research and development efforts involved, such innovations tend to occur in longer innovation cycles. System innovations relate both to subsystems and to the overall system. The aim here is to change and improve existing, complex products in a systematic way. Different aspects of a system, such as technology, processes, regulations, behaviors and environmental factors, are taken into account and specifically changed or integrated. Systems innovation is thus a multidisciplinary and holistic approach to innovation that aims to bring about long-term and profound changes [29]. In particular, when the whole system is considered, substantial innovation in terms of the innovation cycle is also possible.

The quadrant of the business model consists of the axes usability and benefit sharing. Usability in this context describes how often a product is used and by how many people.

A single use stands for the one-time use of a product by only one person. Contrary to this is the characterization of Shared Use. In this case, a large number of people uses a product several times. These products are, for example, means of transport such as bicycles, cars or public transport, but also complex products such as manufacturing machines or production facilities. The idea behind shared use is to make the use of products more efficient while reducing environmental impact and costs. Shared use allows products and equipment to be better utilized, which in turn reduces the need for new resources. Shared use promotes social exchange and collaboration by allowing people to meet and work together who might not otherwise have access to such products. For companies, shared use makes good business sense by increasing product utilization and generating recurring revenue through new business models. Benefit sharing describes the nature of payment terms between provider and user. On this axis, a distinction is made between transactional and subscription-based relationships. Transactional relationships are based on individual transactions, i.e., sales of products or services, where the customer pays for each individual transaction. Subscription-based relationships, on the other hand, are based on a regular income from recurring payments from customers who pay for access to a particular product or service [30]. The main difference between these business models is that the transactional model is based on one-time sales of products or services, while the subscription model is based on recurring income from subscriptions.

The fourth quadrant of the framework is the value creation strategy, which considers both value creation and the life cycle. Value creation is divided into Produce and Operate. These are two distinct phases in a company's value creation process. In Produce, a product is made from raw materials, components, or intellectual property. Value is created by transforming inputs into outputs that have greater value to the customer. Operations, on the other hand, involves delivering the product or a service to the customer and supporting it throughout its life cycle. Value is created by meeting the customer's needs and expectations, installing upgrades and updates, creating a positive customer experience, and building customer loyalty. Life Cycle distinguishes between the contrasting approaches of Replace and Reuse. Replace means that a product is replaced and disposed. Either replacement happens with a new product that performs the similar functions or with a product that offers improved performance or functionality. Reuse, on the other hand, means that the product is reused rather than replaced. To do this, the product is equipped with new functions via updates and upgrades so that the value increases and resale is possible. This approach is representative of the value-enhancing circular economy. The aim of the value-enhancing Circular Production Economy is to extend the life of products and reduce the need to produce new products.

The individual action areas of the framework's quadrants and the enablers necessary to achieve the dimensions are presented in detail below.

4 Field of Action: Product Architecture

The field of action of product architecture aims at a new product modularity. This is a concept in which products are assembled from standardized parts and components. These parts and components are characterized by the fact that they are easy to replace and repair [31]. This enables companies to see a product no longer as an integral product structure, but as a differential structure that is a sum of its parts and components. Thus, at the end of life, the entire product no longer needs to be replaced; instead, damaged components are repaired or replaced. This is intended to reduce waste, increase resource efficiency, and achieve a higher degree of reusability and repair ability in the spirit of the circular economy [32].

In today's world, many companies are affected by the economic challenge of customer demand for increasing product diversity. This forces companies to continuously expand their product range with new product variants. On the one hand, this means that the internal technological diversity has to be extended, but also that the complexity of such products increases. In order to successfully meet this challenge, the concept of new product modularization comes into play. This is seen in the product structure, which has to change back from an integral to a differential product structure. In this way, the modularization of products makes it easy to upgrade. When a defective module needs to be replaced, only that module needs to be replaced. Instead of ending the life of the entire product, this upgrade starts a new life cycle of the product. In addition, the modularization of products also makes it easy to update. When a new module is developed, it is simply integrated into the existing product without having to replace the entire product. The shift towards designing products with increasingly unique features, where each component serves a single function, is illustrated in Figure 3.

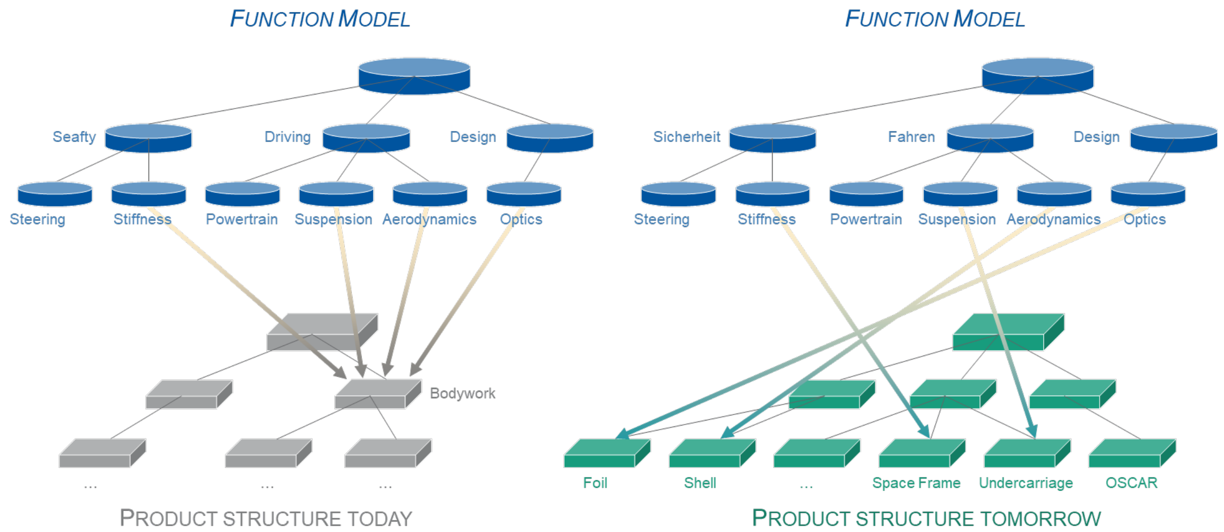

Figure 3: Change in the relationship between the functional model and the product structure

Also in the function model, there is a shift from free features to product functions that are based on a model-based platform. Here, different product variants are produced based on standardized parts. This enables sustainability potentials and cost potentials to be tapped as well as improving the control of complexity [33]. To take advantage of the new product modularity, companies must adapt their product development and product design.

The concrete development and optimization of a model-based platform design is based on the 6R concept (recover, reuse, recycle, redesign, reduce and remanufacture). The 6R concept includes the six stages of the life cycle of materials, which aim to make the product and its design sustainable throughout the life cycle. The new product architecture must be designed in such a way that there are core modules. As Living Standards, these form the basis for modularity over several life cycles. Building on the Living Standards, modules for function upgrades, performance and value upgrades, and product updates are arranged according to their lifecycle. The concept aims to ensure that modules and raw materials are recovered and reused after the first life cycle. Here, it is important to note that the product design must be designed to be functional and resource efficient. In addition, due to the differential product structure and the model-based product platform, the product design must ensure easy assembly and remanufacturing. The *reduce* step focuses on minimizing resource and energy use and waste in a product life cycle. In the *recover step,* products that have reached the end of their life cycle are recovered. Subsequently, such a product is used in the step *reuse to* recover modules or parts so that they are reused in the same type of product. The *recycle* step supports *reuse* by recovering raw materials that can be reused in other products. *Redesign aims* to rework the old product in such a way that a new product is obtained. In the *recover* step, a defective product or a product that is at the end of its life cycle is remanufactured. In this way, the product is restored to a new condition and its life cycle is extended. This is a preferable alternative to the *reuse* and *recycle* steps [34].

MTA Gerüstbau places great emphasis on product innovation in its corporate strategy. Hereby, the company aims to make the products sustainable and climate neutral. Against this background, the principle of new product modularity has been successfully adopted in the product portfolio and are placed in the sustainability core of the product architecture quadrant. A concrete example of such a product is the Meta Multifloor shelving system. This is a shelving system consisting only of the two modules frame and shelf. The modular product structure of the rack allows any extension of the rack. In addition, by using accessories, countless variants as well as special solutions are realized, such as inclined shelving, rim shelving or shelving with open fronted storage bins [35]. Another example of the successful implementation of product modularity is provided by a modular laptop from *Framework.* This laptop has been explicitly designed so that individual parts of the laptop can be exchanged and replaced. The user makes his laptop more powerful or easily exchanges defective parts. Because of this characteristic, this type of laptop has a longer service life than the integrative laptop design [36].

On the one hand, the new product modularity is advantageous for companies and, on the other hand, it makes a major contribution to the circular economy. The use of a modular structure in different product variants is advantageous for a company in that it allows a company to produce more flexibly, faster and more resource-efficiently. An increase in the production of different product variants usually leads to a trade-off between the number of product variants and the operating performance. Product modularity minimizes this trade-off with its positive features [37]. This is realized by using the same modules in different product variants, which allows the company to achieve economies of scale. This enables more efficient production. Furthermore, such modules are usually standardized parts that are produced in large quantities, which also reduces production costs. In addition, the standardization of such modules has a positive influence on the flexibility of the company, since this offers the possibility of component substitution [38].

The differential and "model-based" product architecture enables lower energy and resource requirements in production, making it conducive to the aspect of sustainability. In the case of defective products, individual modules are replaced to restore functionality and thus increase the product's lifetime. Extending product life also leads to a reduction of waste. This realizes additional potential benefits by preventing the need to manufacture a new product in an energy- and resource-intensive manner. The integration of processes for remanufacturing and repairing products further promotes the sustainability of product modularity. Recycling products that have reached the end of their life cycle leads to achieving a closed loop economy. This reduces the use of primary resources and avoids the generation of waste. In addition, the use of recycled materials or modules produces fewer emissions compared to the production of new products, as less energy is required.

In addition, by focusing on individual modules, learning effects are achieved, which save energy and resources in production. By making production more efficient due to the learning and scale effect, greenhouse gas emissions are reduced [33].

Product architecture in the dimensions "Product Structure" and "Function Model" is a significant concept for future sustainable development. The numerous advantages of a new modular product structure in combination with a circular economy are conducive to the development towards more sustainable production.

5 Field of Action: Innovation Strategy

Functional expansion provides an approach for durable products that nevertheless do not hinder technological progress and innovation. In the second product generation, function extension helps to maximize the value retention of the product. A second product generation refers to an improved or extended product from the first generation and thus represents an incremental innovation cycle. Normally, a product experiences wear and tear over the course of its life, which is accompanied by a loss of value. However, not only is the wear and tear negated by extending the functions, but the product can is equipped with current, innovative properties. This not only allows the product to have the same value as at the time of purchase, but also the same value as a newer product has at the time of the functional upgrade. Thus, the value of an upgraded product is not the same as a new product from the same generation, but even the same as a new product from the newer generation. This ensures that the product is not limited to the functions at the time of sale, but is also improved in the future. This is expressed in Systems Innovation, which structures innovations from subsystems to the entire system. In this context, the modular product design is of high importance, as this offers the possibility, with little effort, to implement these changes in the product in subsystems and thereby achieve improvements. This means that the concept of a product having only a fixed set of functions will be abandoned [39].

The companies *Fairphone* and *Shift* already use the concept of modular product construction, thereby ensuring function expansion and value retention in their product. Both companies offer smartphones that have not been glued together. This ensures modular product construction and individual modules such as the battery, camera and screen are replaceable with little effort. Replacing individual modules enables the user to expand functions of the smartphone incrementally and in subsystems, thereby maintaining its value with innovations. On the one hand, this allows the user to save costs, since the modules are cheaper than the price of a completely new smartphone. On the other hand, resources are saved, which is beneficial to the aspect of sustainability [40].

Furthermore, the modular vehicle structure of the Shuttle META from *e.Volution GmbH* represents a good example of this topic (see Figure 4). The modular design of the vehicle offers the advantages that it is particularly durable and also renewable. In addition to the vehicle concept and the low-capital and energy-efficient production in the MicroFactories, the vehicle is remanufactured in an innovative process in the Re-Assembly Upgrade Factory. After each reassembly operation, the vehicle quality corresponds to that of a new vehicle at the current time, thus extending the service life of the individual vehicle. Used components are inspected and remanufactured as needed. If new part quality is not achieved or the energy and resource requirements are higher than for new part production, new parts are processed. This helps to significantly slow down the usual cycle of product utilization. By implementing this concept, *e.Volution GmbH* enables a service life of up to 50 years and achieve resource conservation within the cycle system [41].

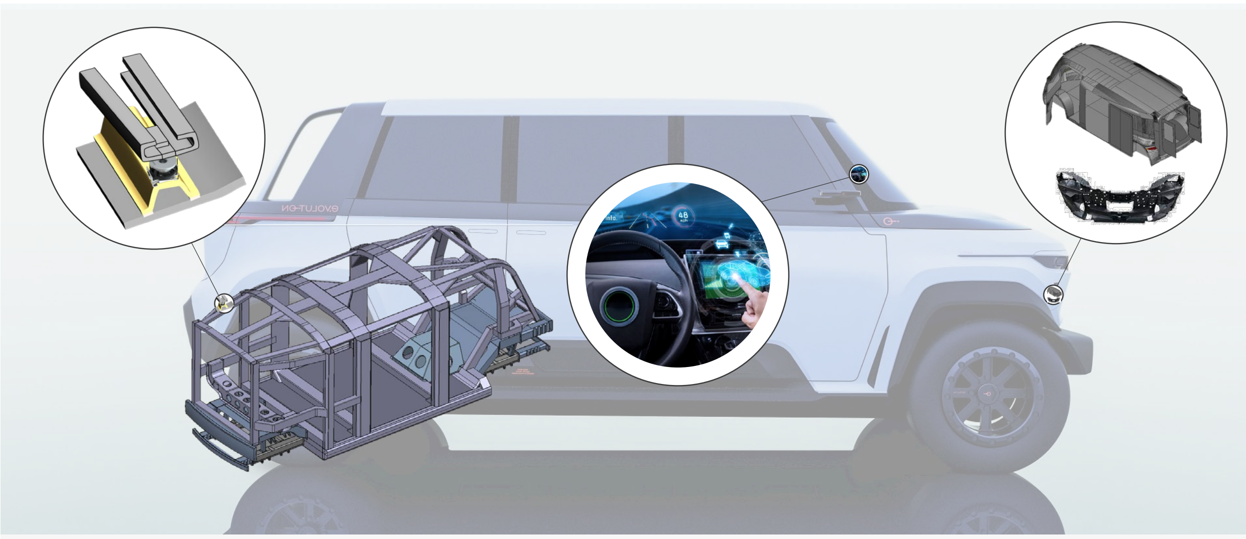

Figure 4: Modular vehicle structure of the Shuttle METAs from e.Volution GmbH (Source: e.Volution GmbH)

The principle of extending functions and maintaining value through incremental innovations of subsystems has many advantages in terms of sustainability. This principle is cou-pled with a modular product design to enable or simplify the process of incremental inno-vation (see Figure 5). By offering the possibility of further developing individual modules in a product, this principle minimizes resource requirements and maximizes service life compared to conventional products. In the case of a conventional product, the customer benefit decreases over the product life until the end of life. Through incremental innova-tion over the entire product life, the customer benefit is increased repeatedly. In this way, product life is extended without sacrificing innovation. For the user, there is no need to buy an expensive new product in order to obtain innovative functions. This also saves resources and energy that would otherwise be associated with new production, since approximately 80% of a product's environmental impact is attributable to the design phase [42].

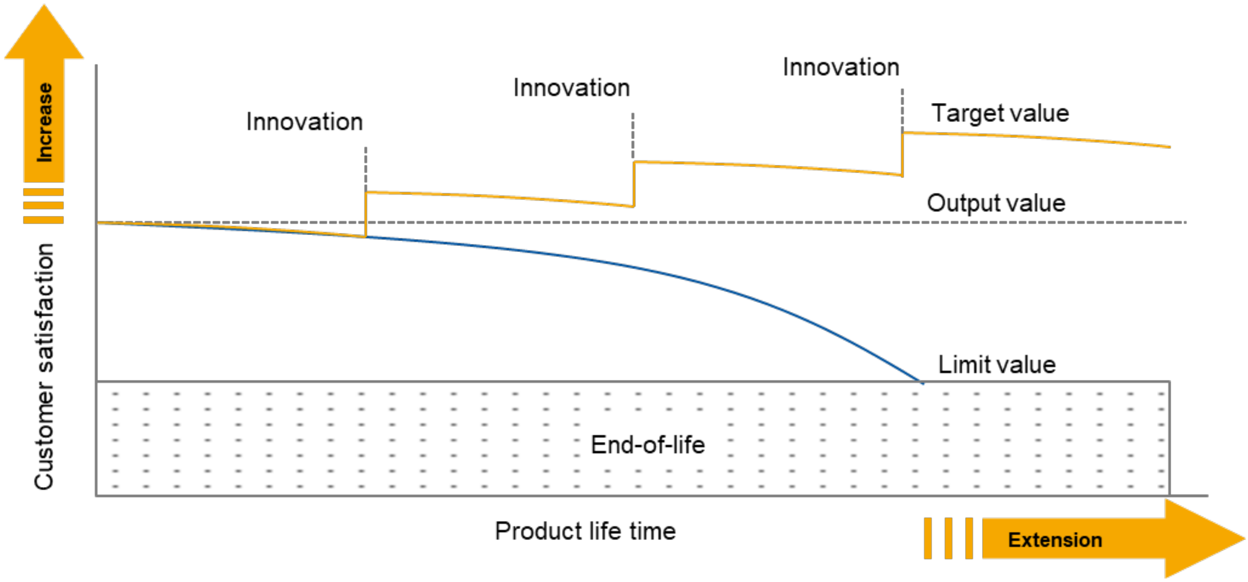

Figure 5: Incremental innovation and value enhancement through upgrades

The associated emission of pollutants are avoided or reduced. The extension of the service life is ensured by the fact that function-critical modules can be replaced. The replacement of modules is additionally advantageous in that it also reduces the generation of waste. This advantage is extended, if this principle is integrated into a circular economy. Modules or subsystems that have been exchanged for innovations are used to recover raw materials and materials. These are reused in other products. The process of reuse is conducive to production efficiency.

6 Field of Action: Business Model

Suitable business models are indispensable for the introduction of a value-enhancing circular economy. Based on business models, long-term strategies are defined and pursued, and the company's resources are deployed in a targeted manner. Each business model must be individually adapted to the company's circumstances and must reflect the company's sustainable goal. In addition, the strategy it contains must be clearly defined in order to ensure goal-oriented action. Thus, a suitable business model must also have long-term sustainability as its goal. In this context, aspects of climate friendliness are given priority over short-term profits.

A value-enhancing circular economy is based on the three principles of waste and waste gas reduction, circular flow of materials and products, and restoration of nature [32]. This is implemented by using resources as efficiently as possible so that they are reused in a closed cycle. Instead of materials and products being discarded or underutilized after a single use, they are shared, leased, reused, repaired, and recycled for as long as possible. Through these types of shared use, the life cycle of a product is increased and resource use is made as efficient as possible. As a result, waste is minimized and resources as well as materials remain in the circular economy as long as possible [42]. Such a reduced use of primary raw materials reduces the emission of exhaust gases in Germany by up to 5.5 million tons, which in turn has a positive effect on the environment [43]. For successful implementation, the right business models must be selected based on the elements of "subscription" and "shared use". In the Framework for Circular Production Economy, the business models are therefore divided into the two dimensions "Benefit Sharing" and "Usability".

Particularly sustainable business models of "benefit sharing", in which products are used particularly efficiently in shared use, are the sharing economy model and the leasing model. The sharing economy model represents a possible business model for implementing a value-enhancing circular economy. This model describes a socio-economic platform that enables users to share goods, services and information with each other (shared use). Instead of a product having to be purchased at high cost (single use), for example, it is shared among the platform users at a lower price. In this case, a product or service is shared between several users. Car sharing is a popular representative of this model. The sharing economy model offers great sustainability potential, as companies or even private individuals who do not need products frequently borrow them. Sharing leads to fewer products being produced and therefore fewer resources having to be used. It also offers the user the advantages that borrowing is cheaper and also increases their flexibility in using such products [44].

In the leasing model, the right to use a product is transferred to a company or an individual for a certain period at a fixed price [45]. After this period, the product is replaced by a new one if desired. Thus, it is clearly classified in the "Subscription" area on the "Benefit Sharing" axis. An example of the application of this model is represented by the company *MIL Maschinen- & Industrieanlagen-Leasing AG.* They provide their customers with such leasing services for a certain period of time [46]. This model allows users to use resources in a more targeted manner. In addition, it ensures that only those resources are used that are actually needed.

In the product-service-system model, as a subscription benefit-sharing model, the lifetime of products is optimized by targeted service activities of the manufacturer. At the core is a network of tangible products as well as service products from actors and a supporting infrastructure to fulfill customer needs. Under this model, a company offers a product and associated service activities to its customers [47]. *Philips Lighting,* among others, follows the product-service-system model with its lighting. The company not only offers the lighting as a product, but also offers related services such as maintenance, inspections, and system optimizations [48]. This model contributes to sustainability in that the manufacturers targeted service activities optimize the lifetime of their products.

When remanufacturing is combined with upgrades and updates, functional enhancements and value increases are enabled. By using upgrades and updates, remanufacturing processes are used to bring old products up to the latest technology. For example, a computer that is no longer up to date could be upgraded by replacing components such as the processor or hard drive to provide better performance. This expands the product's function and increase its value. Another benefit of upgrades and updates related to remanufacturing is that they allow companies to adapt products to new customer markets. For example, if a particular product is no longer in demand or the market is saturated. Upgrades and updates are used to adapt it to the needs of a new market. Finally, upgrades and updates related to remanufacturing also help to extend the life of products. When older products are upgraded, they are just as effective as new products in many cases. In this way, companies extend the life cycle of their products and reduce the amount of waste generated by disposing of obsolete products.

Each model has individual limitations and therefore cannot be applied in every situation. The sharing economy and leasing models are both based on the principle of lending products. The sharing economy is advantageous when a company wants to borrow products on a short-term and flexible basis, whereas leasing is more long-term (subscription). The models use the principle of reusing raw materials and materials (shared use). All these models have the advantage that the reuse of raw materials reduces the need for non-sustainable resources and reduces the waste generated [32]. If possible, the upgrade is the first choice for the models, as this increases functionality and value. Otherwise, the other two models are used. The product-service-system model is used when a company wants to purchase a product while making the most of its lifetime. Based on the advantages of the Circular Production Economy and the associated business models, their importance for the future is clearly emphasized. However, it is necessary to further develop and adapt these business models in order to be able to use them in as many areas as possible. Nevertheless, this is not enough; companies need to adapt their perspective on the evaluation of production before the aspect of sustainability. There needs to be an expansion of assessment dimensions from a purely financial perspective to include environmental, social and governance dimensions. It is crucial that these perspectives do not describe conflicting goals, but are addressed holistically manner through a value-enhancing circular economy and ultimately result in a business advantage for companies.

7 Field of Action: Value Creation Strategy

To realize the new product modularity, not only new development and design strategies are needed, but also industrialized structures to systematically upgrade complex mass products such as cars, household appliances, machines and plants for a second, third or fourth life without customers having to forego the increased performance and attractiveness of newly developed products. The remanufacturing and repair of technological products has significantly decreased over the last 20 years due to the constant new development and production of these technological products. Customers usually decide not to repair a technological product due to a new purchase of the same or similar product. [49] Too high repair costs or a product that cannot be repaired or is too old are in about equal second place as reasons against repair. Initial approaches by companies to bring their technological products back onto the market in a targeted and thus industrialized manner have so far tended to be isolated approaches in the sense of the Value-enhancing circular economy [50].

The industrialization of remanufacturing processes has so far been limited to a few sectors of the economy and is technologically restricted to the remanufacturing of primary materials and materials used in their raw form at the beginning of the product life cycle. These are mainly primary materials such as plastics and metals. The reprocessing of technological products has so far been limited to isolated solutions and niche products [51].

A meaningful paradigm shift toward a value-enhancing circular economy requires more comprehensive measures than these isolated approaches to reducing resource consumption. A reassembly factory is a production facility that specializes in assembling used or recycled parts and components into new products. The process involves several stages. First, sorting and disassembly takes place, where used products are sorted by type and disassembled into their individual parts. This is followed by cleaning and reconditioning. Here, the parts are cleaned and refurbished to ensure that they are in good condition and suitable for reuse. After this, the actual reassembly is possible. The parts are reassembled into new products using special tools and equipment. Finally, quality control is performed. The finished products are inspected and tested to ensure they meet the required quality standards. A possible layout for a reassembly factory is shown in Figure 5 is shown.

To achieve this, it is necessary to consider functional extensions, i.e. upgrades, in the re-production process. Re-assembly upgrade processes save up to 90% of the material and environmental impact of new products and increase the value added per employee, e.g. in vehicle production, by around 30-60%.

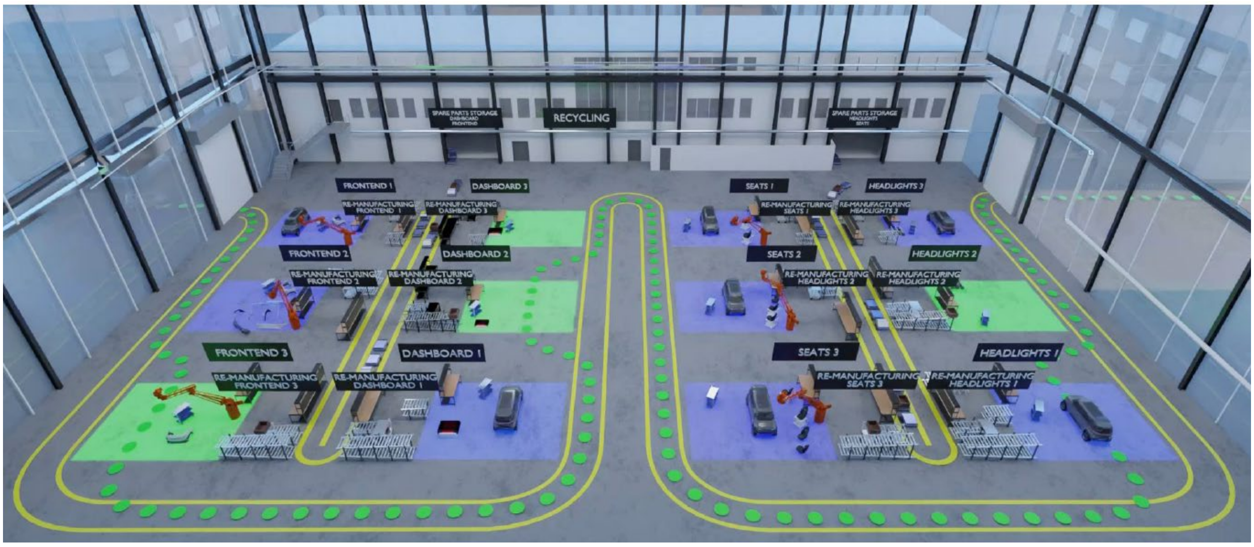

Figure 6: Material flow and stations in a reassembly factory

At first glance, product remanufacturing seems to be economical only for products with a high material value and high initial production and development costs, such as aircraft turbines or cruise ships. A significantly higher degree of industrialization is required to enable the remanufacturing and functional improvement of products with a lower value. This leads to higher utilization of resources and enables similar economies of scale as new production. However, industrialization requires a separation of planning and execu-tion of the necessary activities. This is complicated by uncertainty about the condition and quantity of returning products. Detailed information about the labor time and spare parts required in remanufacturing is not available until after the returns have been inspected, so that detailed planning of production takes place from this point on. The resulting infor-mation asymmetries inevitably lead to higher inventories, process costs and longer lead times.

When short-life products are manufactured in a linear economic system with short-term planning horizons, this leads to production processes and buildings in which short-term profitability takes precedence over sustainability in most cases. Although regulatory and societal pressures are driving manufacturers toward more sustainable practices, there is often uncertainty about where the greatest potential lies in manufacturing and what ac-tions are needed to unlock it. Countering this requires greater transparency of resource use, in terms of both volume and location, as well as the long-term ability to continually adapt buildings to new circumstances. In addition, new or modified metrics help to guide investment decisions toward more sustainable solutions. Potential information asymme-tries in industrial remanufacturing are resolved by setting up cross-lifecycle data struc-tures such as the digital product file. This data set links data from the development phase (bill of materials, interfaces, etc.), production (component properties, process parameters, etc.) and the various usage phases (operating time, load profiles, etc.) across all stakeholders. To achieve this, clear identification of the relevant assemblies and modules and easy access to the data are required.

Industrial remanufacturing is often not yet as automated and industrialized as the initial production of the technological product. One example is the time-consuming removal of "non-detachable" material-locking screws or rivets. New time- and resource-saving processes, such as adaptive automation, must be developed and tested: This is the key to industrializing remanufacturing processes for technological products.

8 Enabler: AI-Based Lifecycle Management

Product Lifecycle Management (PLM) is a knowledge-intensive process that includes market analysis, product design and development, but also production, process development, product distribution, use, but also after-sales service and recycling of a technological product [52]. Due to the large amount of data generated, PLM is particularly suitable for the use of artificial intelligence (AI) or for the use of lower-level methods of AI such as Big Data. The processing of large amounts of data, as they occur in PLM, and the linking of this data with recommendations for action is captured and made transparent with artificial intelligence. [53] For any applications of AI, one first needs a processed data set and defined input and output data. Previous applications of AI in PLM group this input and output data into the three periods of PLM, beginning of life (BOL), middle of life (MOL), and end of life (EOL). The input data in this field of view also range from data on customer requirements (e.g., product function or configurations) to environmental data during use of the product (e.g., conditions of use or duration of use) [54]. The output data, on the other hand, starts with data on design specifications such as material lists or tolerances and ends with data on disassembly possibilities such as disassembly costs or recycling data. The focus in processing the data is on processing using process history methods. [55] Process history based methods require a large amount of historical process data that is annotated in a suitable way. The existing PLM also provides a sufficient basis for this, but it excludes several life cycles of a product or life of a technological product for the time being [56].

In the value-enhancing circular economy, the emerging new life cycles or life of a product generate further data on the actual product, but also on the assembly and its individual components. In order to make the decision between extending the function, maintaining the value or actually ending the lifecycle of a technological product and to process the information and data that are decisive for this, AI-based lifecycle management is also required in the value-enhancing circular economy (Figure 7).

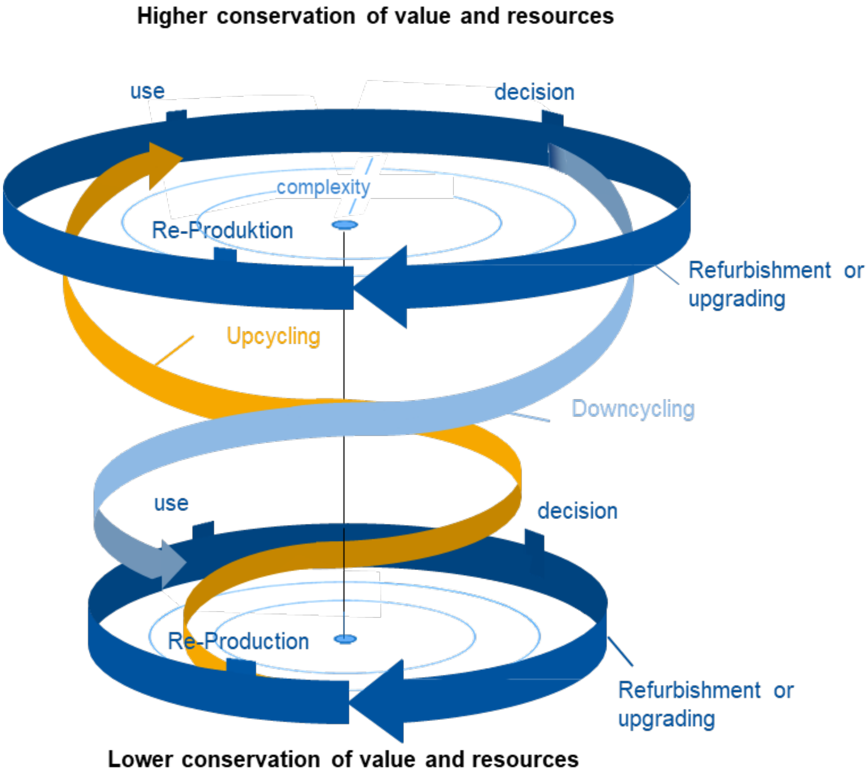

Figure 7: AI-based lifecycle management in the value-enhancing circular economy

In the circular economy, which aims to enhance value, AI-based lifecycle management determines the utilization cycle a product should enter based on its system complexity, current value, and expected lifespan. This decision is made for technological products in order to maximize their value and increase their usefulness over time. The system complexity indicates how complex the technological end product is, i.e. whether it consists of different assemblies, how many and which components technological end product is composed of, and which joining processes or mechanisms were used for the composition. AI-based lifecycle management decides whether a product continues to circulate in its functional level of its current lifecycle or moves to a new functional level, giving it a second, third or fourth life. This decision-making takes place at all functional levels, so not only the technological product itself is considered, but also individual assemblies within the product, down to small components.

The infrastructure of manufacturing companies for the targeted aggregation and processing of information across multiple data sources and the creation of real-time decision-making bases for cross-domain issues, also known as the "Internet of Production", forms the basis for a more efficient and value-enhancing circular economy as well as AI-based LCM (lifecycle management). To take full advantage of these approaches, they need to be further developed and implemented. A digital product file (Figure 8) that documents the entire product lifecycle helps companies gain a more comprehensive overview of their products and make better decisions by enabling transparency and traceability of products. In principle, the development of the digital product file is subject to high requirements in terms of precise documentation of the processes and associated data, continuous real-time documentation, but also the guarantee that the recorded data is tamper-proof.

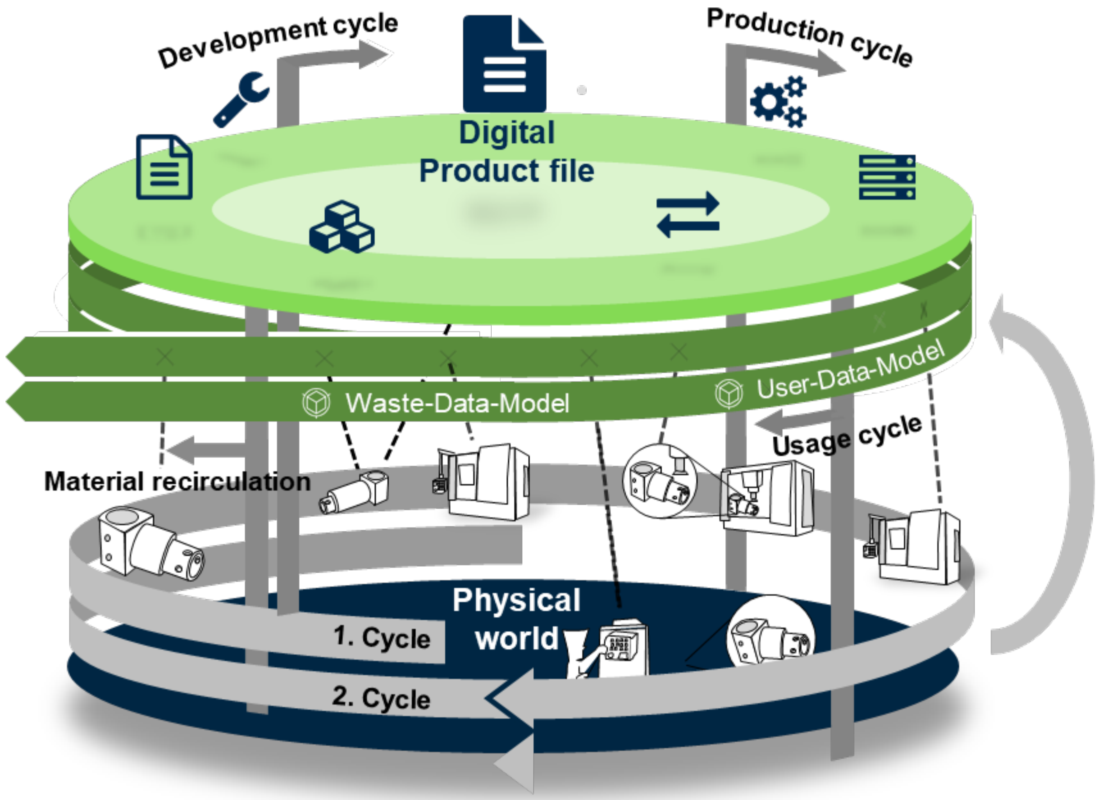

Figure 8: Digital product file in the value-enhancing circular economy

For the value-enhancing circular economy, the digital shadow is extended to include the digital product file. The digital shadow thus exclusively represents the connection between the physical world and the digital product file in the value-enhancing circular economy. The digital product file is initially fed into the development cycle with information from the product data set, such as material data, parts lists or repair instructions. Moving on to the production cycle, disassembly or reassembly instructions are then stored, as well as user data and product history data. Additionally, in the value-enhancing circular economy, data on predecessor and successor components is added. The storage of this data is the enabling of multiple usage cycles of individual products, but also their parts and individual components.

Crucial for the AI-based processing of the lifecycle data of the value-enhancing circular economy is this digital product file, which stores all lifecycle data and does not distinguish between the different phases of PLM, BOL, MOL and EOL, as is the case for conventional PLM. These phases merge for the PLM of the value-enhancing circular economy and are different for the individual assemblies and components of product. Figure 9 shows the required information flow during the lifecycle of the value-enhancing circular economy and the resulting cloud-based emergent evaluation.

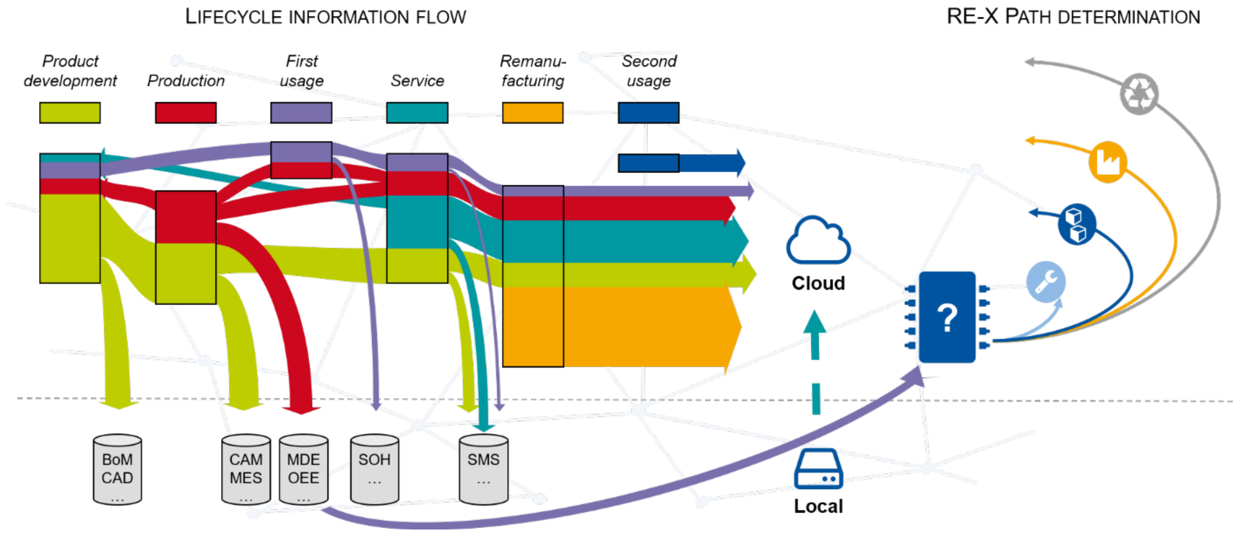

Figure 9: Lifecycle information flow and cloud-based emergence evaluation

The central open-source cloud collects all the data needed for classification and identification of the sustainable Re-X scenario. The distinction to be made here is that the data flow does not stop with the first use, but a second, third or fourth use of the final product, its assemblies or components follows on from the service. This must also be reflected in the storage and processing of the data. Decisions are made between the possible further processing operations for the final product, its assembly or individual components.

By using AI-based lifecycle management, companies are able to better monitor and evaluate the lifecycle of their products, components, materials and processes. This enables them to identify and implement value- and function-enhancing measures in a timely and optimal manner to increase efficiency and profitability while minimizing environmental impact. The application of AI enables improved analysis of data and accelerated decision-making based on automatically generated insights and predictions. The decisive factor here is the development of a digital product file in an Internet of Sustainable Production, as a further development of the Internet of Production, which stores, updates and makes available the database for AI-based lifecycle management.

9 Summary

Companies are under enormous pressure to make their production fully sustainable, as a broad public from politics, customers and society now demand not only increased production efficiency but also processes and products without negative environmental impact. This requires new approaches that expand the understanding of sustainable production to include that of a value-enhancing circular economy. Thus, new aspects are emphasized so that long-lasting products are profitably offered on the market by means of function enhancement. In addition, companies must align their strategy with this new understanding and focus on product architecture, business models, innovation and value creation strategy that reflect the characteristics of a value-enhancing circular economy. This alignment enables the development of products that are able to offer a model-based platform for various functionalities by means of differential modularity. In addition, companies achieve continuous improvement of subsystems of a product through short, incremental innovation cycles. This approach is further supported by a subscription-based customer relationship encouraging shared use of products by other customers. In this way, value creation expands from the actual production to the operation of the products. Such operation also enables and motivates the reuse of products over a long service life. Moreover, a globally networked Internet of Sustainable Production is essential so that this is mapped in terms of information technology.

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4.2 Green Re-Assembly Upgrade Factory

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Abstract

Green Re-Assembly Upgrade Factory

This article discusses the need for a paradigm shift towards a more sustainable circular upgrade economy, highlighting the importance of implementing comprehensive measures instead of isolated approaches. It proposes the Green Upgrade Re-Assembly Factory to sustainably upgrade complex mass-produced products for multiple life cycles without compromising their performance and attractiveness. The article identifies the challenges faced in re-assembly processes, such as uncertainties in the quality of return products and lack of sustainability transparency. It suggests solutions such as the Digital Product Record and flexible and adaptable process designs. Furthermore, transforming production buildings into climate-neutral green factories designed to have the longest possible life cycle and most resource-efficient operation is necessary. Using prominent industrial examples, the authors show that both the transformation of a company to a circular production approach and the transformation of a factory to a climate-neutral green factory can succeed profitably – already under today's conditions.

Keywords: Re-Assembly, Green Factory, Re-Manufacturing, Circular Economy, Sustainable Production

Kurzfassung

Green Re-Assembly Upgrade Factory

In diesem Artikel wird die Notwendigkeit eines Paradigmenwechsels hin zu einer nachhaltigeren Upgrade-Kreislaufwirtschaft erörtert. Der Fokus liegt dabei auf der Bedeutung der Umsetzung umfassenderer Maßnahmen anstatt einzelner isolierter Ansätze. Es wird die Green Upgrade Re-Assembly Factory als Lösung für die nachhaltige Aufwertung komplexer Massenprodukte für mehrere Lebenszyklen vorgeschlagen. Der Artikel zeigt die Herausforderungen der Re-Assembly-Prozesse auf (z. B. Unsicherheiten bei der Qualität der Rückläuferprodukte sowie mangelnde Nachhaltigkeitstransparenz und schlägt Lösungen wie die digitale Produktakte und flexible und anpassungsfähige Prozessdesigns vor. Darüber hinaus wird in dem Artikel dargelegt, dass auch eine Transformation von Produktionsgebäuden in langlebige sowie klimaneutral und ressourceneffizient betreibbare grüne Fabriken notwendig ist. Anhand namhafter Industriebeispiele wird gezeigt, dass sowohl die Umstellung eines Unternehmens auf einen zirkulären Produktionsansatz als auch der Umbau einer Fabrik zu einer Net-Zero-Fabrik profitabel gelingen kann – bereits unter den heutigen Bedingungen.

Schlagwörter: Re-Assembly, Green Factory, Re-Manufacturing, Kreislaufwirtschaft, Nachhaltige Produktion

1 The need for a value-adding circular economy

Based on the "take-make-dispose" principle, the linear economic system depletes finite resources and is not sustainable. More comprehensive measures must be taken to achieve a more sustainable circular economy. Production technology can achieve enormous sustainability potential when complex mass and serial products such as cars, household appliances, machinery, and equipment are systematically qualified for a second, third, or fourth life. It is important to consider functional enhancements in the reproduction process. In this way, customers do not have to forego increased performance and attractiveness of newly emerging products. By replacing only about 10 % to 30 % of components, complex serial products can achieve almost the same value as a new product and save up to 50 % of the resources and emissions used in industrial production [1]. Depending on the product, two to three times the margins of these more sustainable upgrade products can be achieved per re-processing cycle compared to new, classically produced products.

A paradigm shift towards the closed-loop circulation of materials is one of many challenges companies face in sustainable production [2]. The product-related requalification and extension of functionality must be located in a building that is equally function- and value-enhancing, with the longest possible life cycle and most resource-efficient operation. In particular, transforming existing factories into long-lasting, climate-neutral green factories is relevant. If successful, both economic and strategic advantages can be achieved. By generating renewable energy on-site, 70 % to 90 % of the energy supply costs can be saved already today. In addition, the production site-related resilience and security of supply increase. Efficiency gains through continuous monitoring of building operation data have not yet been considered for this estimation.

Based on prominent industrial examples, this article shows that both the outlined value- and function-enhancing circular economy and the climate-neutral transformation process of a factory are already profitable under current conditions.

Section 2 discusses the challenges and solutions for a value- and function-enhancing circular economy, and section 3 describes how to transform existing factories into long-lasting and climate-neutral green factories. Section 4 combines these approaches into the "Green Upgrade Re-Assembly Factory".

2 Upgrade Re-Assembly Factories enable highly profitable functional and value enhancements

This section discusses the applicability of Upgrade Re-Assembly Factories, presents possible processes and organisational forms, and derives the resulting requirement for a digital product file as a key enabler of the value- and function-upgrading circular economy.

2.1 Value- and function-enhancing circular economy is not only possible for cost-intensive capital goods

At first glance, product reprocessing with simultaneous functional and value enhancement seems economical only for products with a high material value and increased production and development costs, such as aircraft or cruise ships. For products of this type, usage cycles over several decades are standard. To adapt them to changing conditions, nevertheless, new functions and design adjustments are repeatedly introduced into the products over the years to maintain usability and value. An example is the modification of passenger aircraft cabins: These are fully renewed approximately every seven to ten years in the life cycle of an aircraft to offer passengers increasing comfort without having to replace the entire aircraft. In shipbuilding, extending ships during their lifetime to increase capacity or the conversion of conventional propulsion systems to sustainable energy sources is the industry standard. For these functional extensions of products in comparatively small quantities, specialised companies work with high manual effort and highly skilled personnel. The processes are comparable with repair stores or the organisation of construction site assembly. They, therefore, cannot be transferred to series products such as those in the automotive, household appliance or building technology industries.

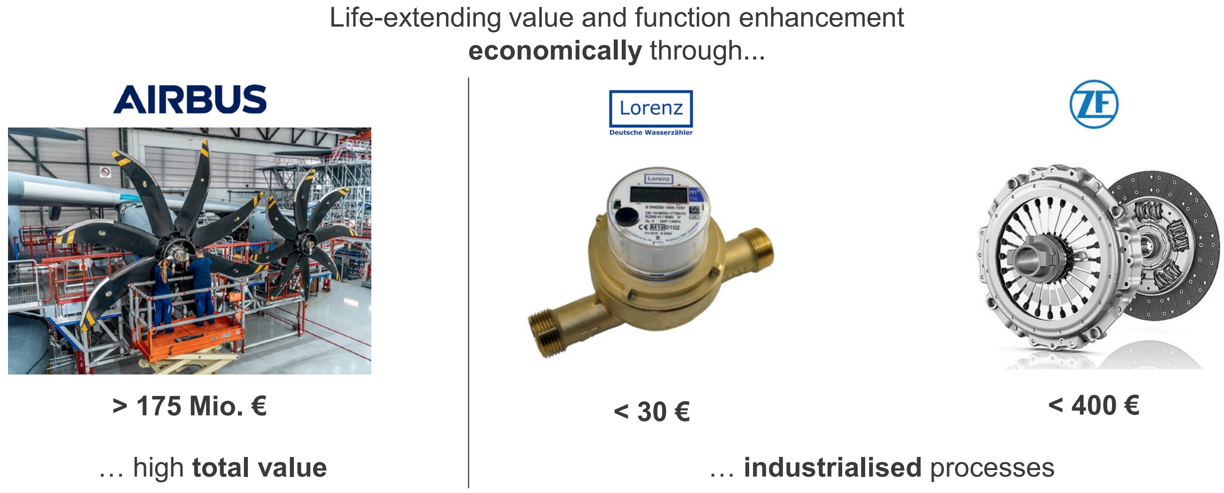

Figure 1: Comparison of product categories for life-extending value and function enhancement

To enable the possibility of reprocessing for products with a comparatively lower value (see Figure 1), a change in the business model towards controlled return options is necessary. By cooperating directly with customers and interpreting them as "our suppliers of tomorrow", the company Lorenz GmbH & Co.KG, for example, enters a strategic partnership with the customers of the water meters it manufactures. Through this partnership, approximately 500,000 water meters, sold at roughly 29 €, are recycled yearly. ZF Friedrichshafen AG also recovers and remanufactures about 10,000 tons of clutch systems and torque converters for trucks and cars worth <400 € each alone in their Bielefeld location from customers through cooperation. They employ approximately 1,800 employees in 25 remanufacturing plants worldwide.

Special attention must be paid to increasing functionality in the re-assembly process to enable technological progress for customers despite reusing old parts. This ensures the attractiveness of re-assembled products. For example, in reprocessing clutches, ZF Friedrichshafen AG applies new coatings based on the latest technology, thus achieving wear resistance at the level of a newly developed product. In the case of clutches, ZF Friedrichshafen AG can also adapt the spring characteristics of the clutches by changing the pitch circles of disk springs, thus adapting the product's function to the changed customer requirements.

A significantly higher degree of industrialisation is required to enable such a function- and value-enhancing preparation of series products with a comparatively lower value. As with classic linear production, industrialisation reduces costs through economies of scale and offers products more attractively to the customer. Dedicated Upgrade-Re-Assembly Factories, where sorting and cleaning, dis-assembly and final assembly of the products occur, are necessary for this industrialisation (see Figure 2). The following section, therefore, describes how such industrialisation of re-assembly can be designed.

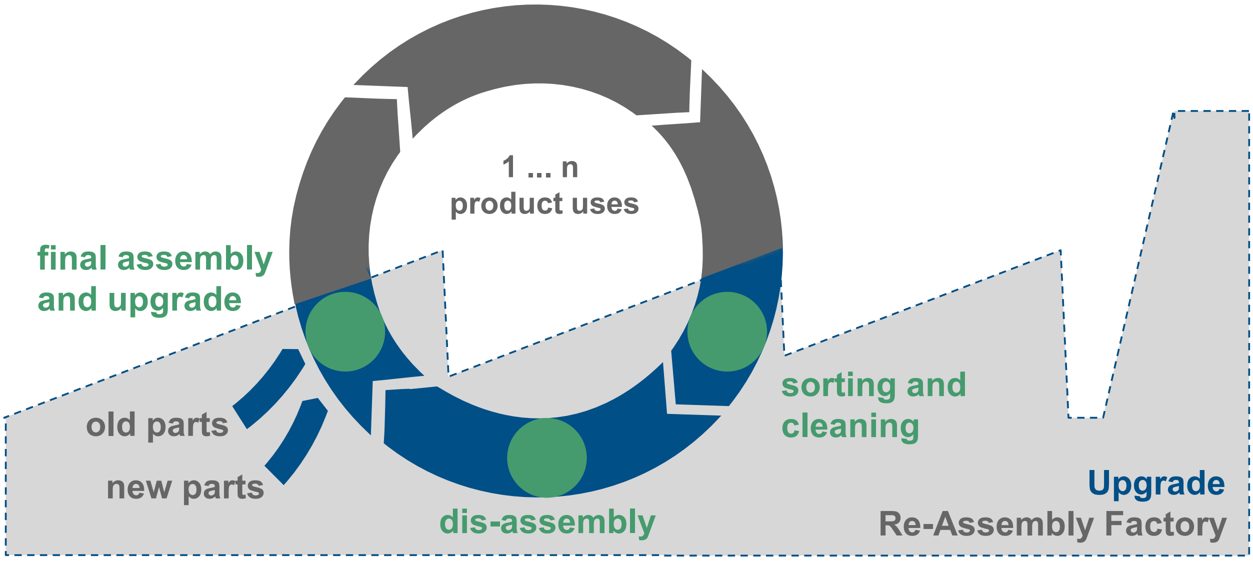

Figure 2: Upgrade Re-Assembly Factory

2.2 Industrialization of processes enables profitable reprocessing and a circular upgrade economy

The industrialisation of production leads to higher output quantities with decreasing resource input per product. For this purpose, the manufacturing and assembly process is subdivided into standardised work steps, which are optimised with regard to the use of resources. Most serial and mass production processes are highly industrialised to be competitive in the linear economy. Industrialisation always makes sense if the initial resource input for optimisation per work step is lower than the sum of the saved effort in production resulting from economies of scale. [3] Such a consideration must also take place in circular value creation. In addition to the standardisation of work steps, the optimisation of material flows and the (partial) automation of work steps are decisive.

In *Figure 3*, a generic re-assembly process is shown. This consists of cleaning, inspection, dis-assembly, re-assembly and the final inspection.

These steps can vary in sequence and frequency depending on the product. For example, it can make sense to dis-assemble a product before cleaning it to sort out obviously defective products, thus reducing the total number of cleaning processes.

In some cases, a sorting step is added before cleaning. To reduce the hurdle of return for customers, Lorenz GmbH & Co. KG, for example, accepts unsorted products and takes over the sorting into scrap and water meters to be further processed. This ensures that customers have the lowest possible barrier to return products to achieve the company's target return rate of 80 %. As a welcome side effect, this also ensures that other returned products are adequately fed into recycling. A return to the corresponding manufacturers for the reassembly of these products is partly taking place and is being discussed with further manufacturers.

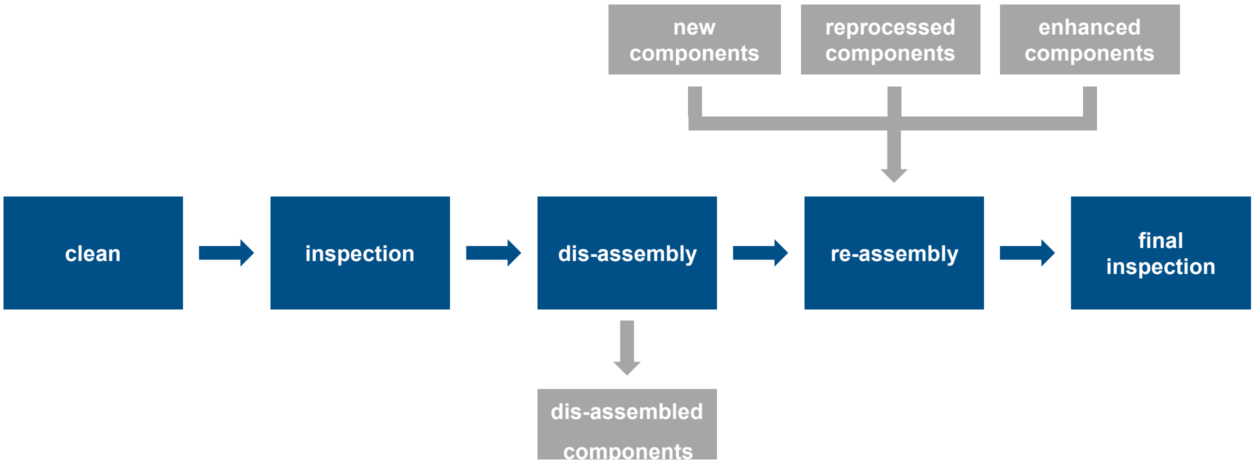

Figure 3: Generic re-assembly process

In the following cleaning step, the products are freed from dirt, etc., to inspect or dis-assemble the components. At ZF Friedrichshafen AG, this cleaning of the components takes place at a later stage with individual components. It is automated through washing and continuous blasting systems. This automation enables a reduction of manual cleaning steps and thus significantly increases process efficiency. In the inspection stage, the products are sorted and checked for suitability for further processing. The sorting focus must be on previously defined components as the decision is made whether to dismantle these components in the further process. Some components cannot be visually inspected for their condition. These include electronic components such as circuit boards. These must either be tested in the device with special test equipment or measuring devices, or dis-assembled in the next step and tested by the supplier.

In dis-assembly, previously defined components and parts are removed from the product so that they can be fed to further reprocessing steps. Dis-assembly occurs based on decisions made during inspection and can vary depending on the product's condition. During reassembly, components or assemblies are mounted into the *core*, the product from which the components were dis-assembled. Depending on the configuration required by the customer, these can be remanufactured or new components that are either identical in construction to the previously dismantled components or newly developed components with a functional enhancement. Finally, in the final acceptance test, the products are subjected to quality tests with requirements at least equivalent to those for a new product and are packaged for delivery.

The final test step plays an important role, especially for products that must be calibrated or certified, ensuring that the product may also be used for the intended purpose. To ensure the most efficient testing possible, Lorenz GmbH & Co. KG relies on a test stand developed in-house, in which a previously defined quantity of water passes through a large number of water meters to determine their measurement deviation. Here, devices from new and old parts are tested equally, with similar measurement results.

In linear production, the output varies in quantity and quality of products, leading to challenges in production planning and design. In re-assembly, the variance in customer demand remains unchanged but is augmented by a variance in input because the condition and quantity of returns delivered are uncertain. These uncertainties have a direct impact on the planning and control of production. Since the exact condition of the cores in many applications can only be assessed at the plant during inspection, early detailed planning is impossible. To fully counteract this delay in providing information, a cross-lifecycle digital illustration of the product, including the creating processes, is necessary, see section 2.3.

Yet, re-assembly is possible even without this continuous digitisation. High flexibility and robust processes are essential for this. An example is the implementation of dis-assembly with increased use of manual labour and semi-automated processes at the ZF Friedrichshafen AG plant. There, employees can react flexibly to the variance in the incoming components at the dis-assembly stations. At Lorenz GmbH & Co. KG, components are dis-assembled with a high use of employees. Due to the lower material input compared to linear production, this manual effort is still profitable. Margins can be doubled or tripled compared to new production. Furthermore, this combination leads to the preservation of highly skilled jobs in the manufacturing industry in the high-wage location Germany.

It is also possible to respond to the variance in the plant's input by using different material flow and dis-assembly concepts. One variation is to dis-assemble products to a predefined state regardless of condition (see Figure 4, run dis-assembly to the end of the top arrow) to allow for better standardisation of dis-assembly and the subsequent steps. In this way, ZF Friedrichshafen AG enables the automation of the cleaning process.

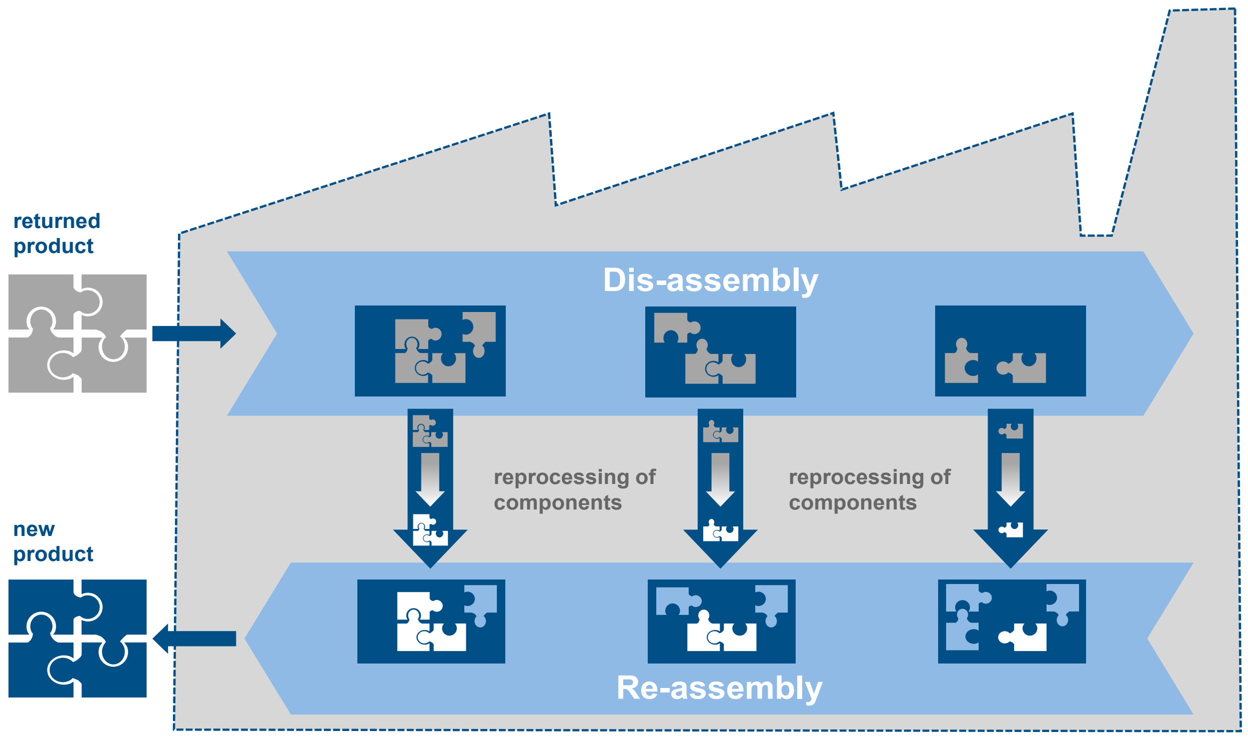

Figure 4: Dis-assembly and re-assembly

Another variation is to dis-assemble the products only as far as necessary and thus to replace only defective components (see Figure 4, for example, up to the second dis-assembly step and Figure 5). Unnecessary steps can be skipped, resulting in a more efficient overall process. At the same time, different functions can be added to the core by performing individual reprocessing steps according to the situation, see Figure 5.

A different concept is the combination of manufacturing and assembly steps of old and new parts. If, for example, certain dis-assembly, assembly or manufacturing steps are only carried out for a smaller number of units, existing automation solutions from linear or primary production can ensure the maximum utilisation of resources. For example, ZF Friedrichshafen AG uses the same robots for the reconditioning of pressure plates for the production of new parts and thus achieves the same production quality and higher utilisation of capital-intensive equipment (see Figure 6).

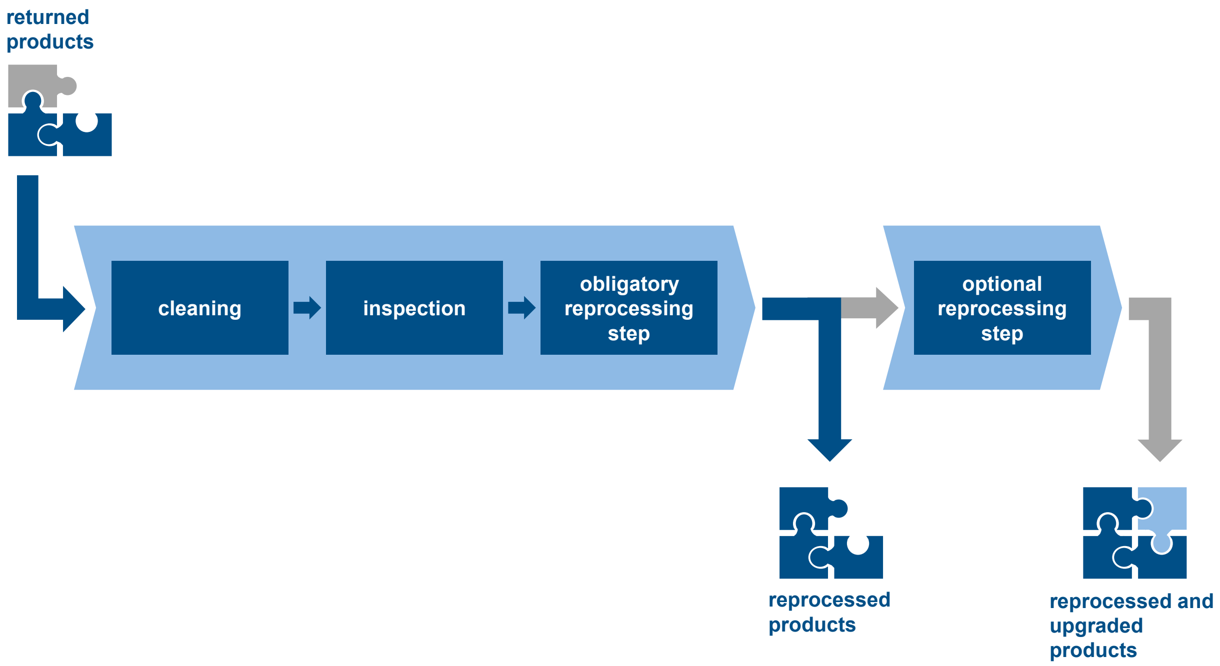

Figure 5: Separation in obligatory and optional reprocessing steps

In addition to efficient assembly and dis-assembly, industrialised manufacturing crucially relies on efficient material supply. A certain planning lead time is necessary to react to the fluctuating parts requirements due to the varying conditions of the incoming parts, even with low inventories. Due to the delivery times of spare parts, it is necessary to carry out material planning and trigger purchase orders even before the products are inspected. This time offset separates planning from execution, as in linear production. The information uncertainties created by forecasting inevitably lead to higher inventory levels, process costs and longer lead times than in linear production. To minimise these side effects, they must be reduced through digital cross-lifecycle data continuity.

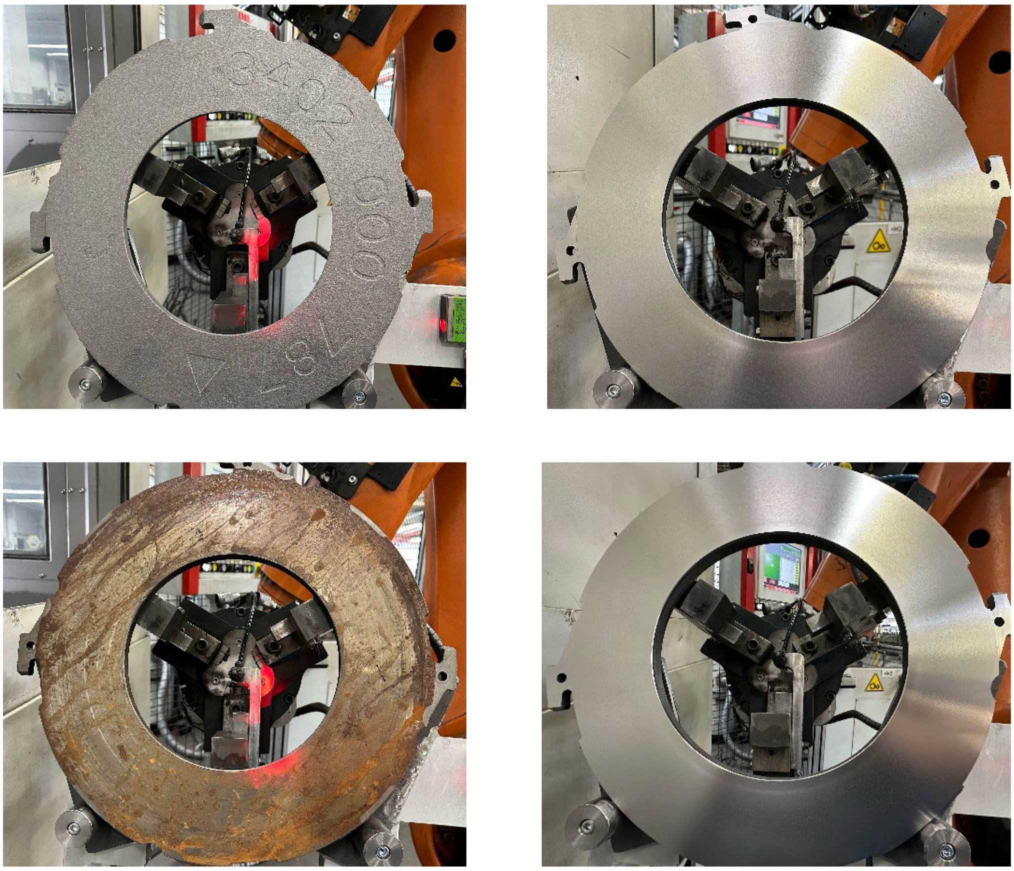

Figure 6: Automated process in jointly used robot cell for new part production and reconditioning

2.3 The digital product record enables cross-lifecycle information singularity and, thus, the reduction of information asymmetries

In re-assembly, the component availability and the component quality of the returned products depend on the individual product life cycle. This resulting uncertainty about the quality of the returns can be reduced with information from the use phases [4]. This allows the quality or usability of the returns for re-assembled products to be estimated, process sequences as well as component yields to be determined, and thus re-assembly costs as well as inventory levels to be predicted and finally reduced.

With only a few well-chosen pieces of information, rough planning for the process steps of re-assembly can already be done. For example, the wear of truck clutches depends on the geographical area of vehicle use, e.g., mountain areas vs urban traffic. Information about the primary geographical location of truck use would enable ZF Friedrichshafen to categorise clutches even before disassembly. The amount of cleaning required for water meters returned to Lorenz GmbH & Co.KG depends on the hardness of the water flowing through them. Therefore, geographical information about the previous installation location of the product would help Lorenz GmbH & Co.KG in planning. Because of the high complexity of the reverse logistics process, in which additional service providers may be involved, such information transfer is rare today. This information asymmetry between supplier and purchaser of old parts causes costly checks. In addition, some processing steps could even be avoided without this information asymmetry.

A cross-stakeholder and cross-lifecycle information singularity is necessary to overcome these information asymmetries: the so-called *digital product record* [5]. It combines data from the development phase (parts lists, interfaces, etc.), production (component properties, process parameters, etc.), and n use phases (service life, load profiles, etc.) and thus extends the digital product passport, see Figure 7 [6].

Unlike classic part lists, however, the digital product record is an emergent document. This means that a change history exists for all elements. Therefore, if a component or part is replaced, both the old and the new element are documented in the digital product record. In addition to the initial manufacturing or assembly date and the subsequent replacement dates in an Upgrade Re-Assembly Factory, a variety of other metadata can be stored in the product record for each element of the product structure. Thus, the product structure already shows the central part of the product life cycle. [7]

Partial information, for example, from the product's development phase, must be non-public, refined or encrypted in this context to protect trade secrets and secure competitive advantages.

For this purpose, a unique designation of components etc., using data matrix codes, for example, is necessary to ensure cross-company usability. In the future, adapted solutions from SAP based on their *Green Token* or *Business Network Material Traceability* technology could be used for this purpose.

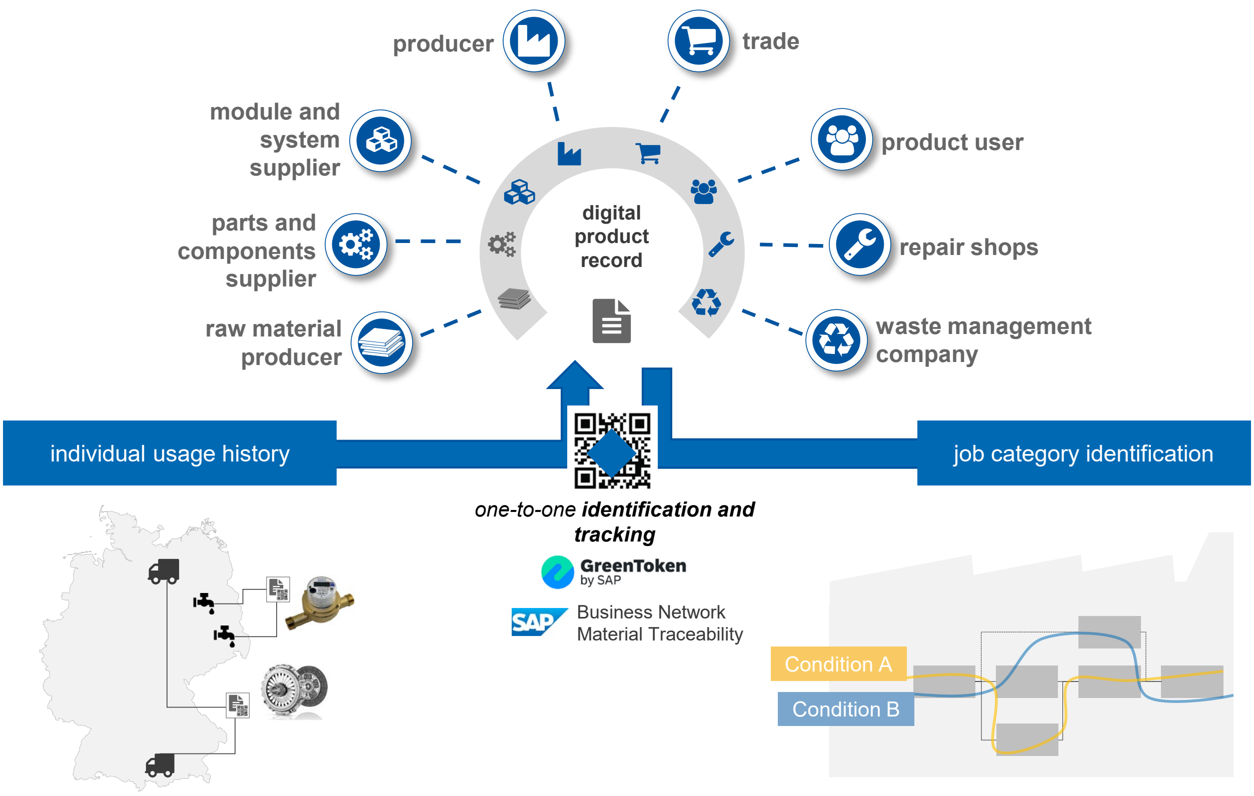

Figure 7: Application example of the digital product record

3 The profitable transformation to Green Factories succeeds in brownfield locations

The following section focuses on the ecological sustainability of the Green Upgrade Re-Assembly Factory and demonstrates that transforming existing factories into Green Factories is profitable. As in the previous section for the product side, a life cycle model is developed from the factory side (see section 3.1), which describes this transformation and upgrade of factories (see section 3.2). Likewise, this section addresses the centrality of data continuity across stakeholders and focuses on the method of *Building Information Modeling* (BIM, see section 3.3).

The company Phoenix Contact GmbH & Co. KG, examined regarding its locations in Bad Pyrmont and Blomberg, provides practical examples of successfully transforming existing factories into Green Factories. An initial determination of the company's strategy (*X-Degree Compatibility Strategy*, XDC Strategy) laid the foundation for the transformation towards climate neutrality. The XDC model uses scientific insights and legal requirements to assess a company's impact on climate change. The climate metric indicates how much the Earth will warm by 2050 if all companies operated with the same emission intensity as the company under consideration. The calculation is based on the emissions required to generate 1 million euros of gross value added between a base year and 2050. The overall approach considers all emissions, including direct emissions from owned or controlled sources (*Scope 1*), indirect emissions from purchased energy (*Scope 2*), and emissions from the company's supply chain (*Scope 3*). [8]

Phoenix Contact specifically assigns the different emission scopes as follows. Scope 1 includes operating buildings and vehicles. Purchasing electricity, heating operation, and cooling for self-use are part of Scope 2. Scope 3 includes materials, logistics, employee mobility, and business travel. Phoenix Contact follows the vision of an All-Electric Society for the transformation: “Renewably generated electrical energy is available worldwide in sufficient quantities and completely economically" as the primary form of energy. The basis for this is that all sectors of the economy and infrastructure are interlinked, i.e., fully electrified, networked, and automated. [9] Intelligent energy management systems can then optimally control energy flows and avoid transportation as well as efficiency losses. The goal is to provide green electrical energy reliably wherever it is needed [10].

3.1 A new model for longer life cycles of resource-efficient green factories

To fully realise the potential for sustainability in industrial production, more than the product life cycle extension through re-assembly and upgrade processes is required. Additionally, the life cycle of the actual factory must be optimised holistically by realising Green Factories that are as long-lasting and resource-efficiently operable as possible. Factories are considered long-lasting when they allow for repeated upgrades to adapt to changing requirements – just like the products manufactured within them.

The literature presents various approaches to describing and dividing the life cycle of factories. Generally, all approaches divide their life cycle into three main phases: factory planning and realisation, factory operation, and factory reconfiguration and dismantling. Within these main phases, the approaches distinguish additional detailed phases. MÜLLER ET AL. consider the construction of the factory separately from its planning. [11] NEUHÄUSER ET AL. identify another phase in the factory life cycle, the so-called renovation or re-planning. [12] This allows for a more in-depth examination of a factory's repurposing, transformation, and upgrading and is, therefore, the approach chosen for this article. DOMBROWSKI ET AL. distinguish four factory planning phases and obtain a total of seven life cycle phases [13]. Such a detailed examination is not helpful within the scope of this article, as it focuses on the practical implementation of the most significant sustainability potential through the climate-neutral transformation of existing factories.

Therefore, the authors conceive the factory life cycle as an overarching three-phase model divided into detailed phases. This results in five phases, which do not follow each other directly. First, they are divided into an outer cycle of *Greenfield* (planning and realisation) over *Brownfield* (realisation and operation) to *End of Life* (operation and dismantling). The phases of the outer cycle merge into one another. The brownfield phase is additionally assigned its own inner cycle, which can be repeated several times: requirements for the factory arising from its operation are planned and realised as an upgrade of the factory itself (see Figure 8). The initial planning of a factory is explicitly distinguished from its upgrade planning. In this model, the overall lifespan of a factory is extended with the number of iterations of the inner brownfield cycle – i.e., with the number of factory upgrades.

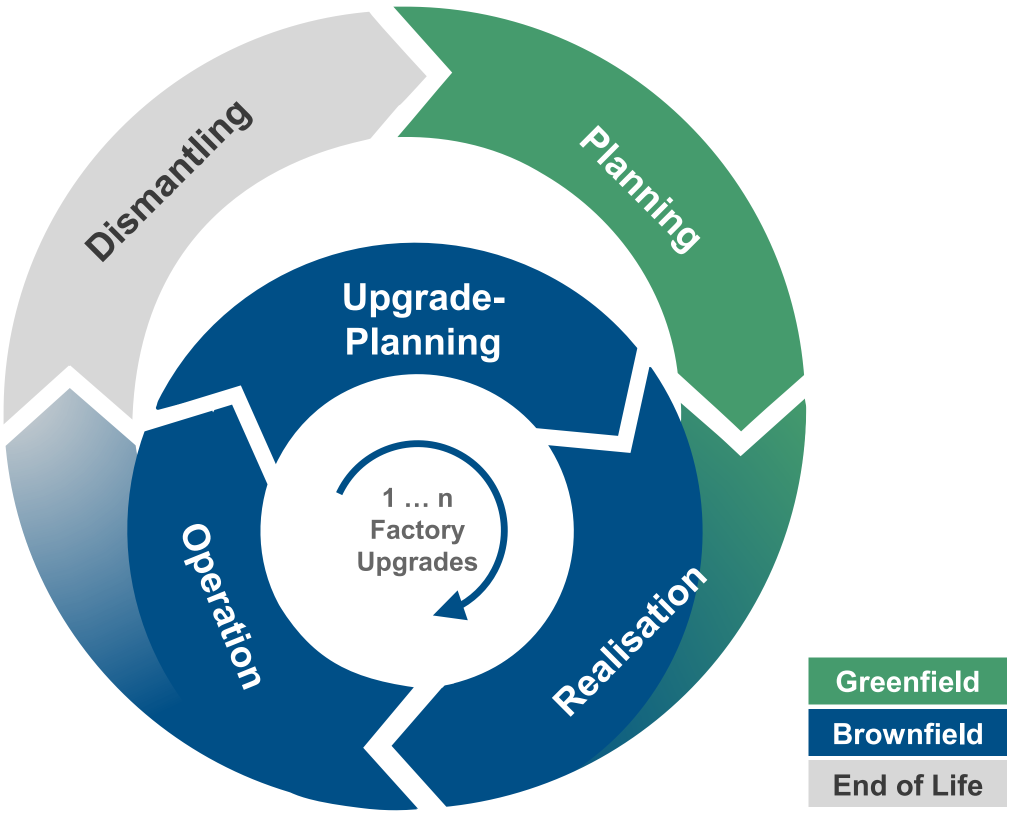

Figure 8: Representation of the factory life cycle, including multiple brownfield upgrades

The derived life cycle of a factory starts with its planning. This is assigned to the greenfield phase because every factory was initially planned on a vacant lot. The factory planning phase includes, for example, the determination of location, production processes and equipment, personnel requirements, and building requirements. In this phase, the expected costs and the factory construction timing are also determined, which are often missed with traditional factory planning methods [14]. Digital and networked planning, for example, through BIM-based building twins, can prevent planning errors and the resulting waste of time or materials. In addition, the other phases of the factory life cycle benefit from this foundation (cf. section 3.3).

The realisation phase follows the factory planning phase: The factory is built and furnished. Realisation starts with site preparation and equipment, while approval issues are still assigned to planning. Waste prevention or suitable waste sorting directly on the construction site can reduce the CO_2 emissions of the realisation phase. Construction site logistics can benefit from optimised transport routes and the electrification of logistics chains: electrically powered construction site vehicles can reduce not only CO_2 but also particulate matter and noise emissions. [15], [16] Realisation includes installing production facilities, offices, staff rooms, (waste-) water systems, machinery, and electricity. In this phase, the reuse of materials and furniture, in particular, can contribute to a climate-neutral Green Factory. The realisation phase ends with the factory's completion and the production commissioning (including ramp-up). During the initial realisation of the factory, the transition from the greenfield to the brownfield phase takes place.

In the following, typically most extended factory life cycle phase, the factory is operated for its intended use. In addition to the routine maintenance of the building, continuous monitoring of production and building operating data is necessary to design and evaluate optimisation measures for a net-zero factory. These include, for example, the detection of line losses, increasing energy efficiency, avoiding waste, increasing plant efficiency, or reducing the consumption of auxiliary and operating materials. If it turns out during factory operation that the production building can no longer be used, the building is dismantled, and the property is repurposed. Otherwise, several upgrade cycles follow, in which the brownfield factory adapts to changing requirements (cf. section 3.2).

In the dismantling phase, the factory is shut down and demolished. When the buildings and facilities have been completely removed during dismantling, the site is recultivated, and the remaining environmental impact is minimised. Ideally, all factory components should be recycled, processed, or directly reused. Such reuse of factory components can be implemented within the framework of the *Cradle-to-Cradle principle*. Cradle to Cradle is a sustainability concept aiming to design products and materials to be reused, recycled, biodegraded, or otherwise returned to their natural cycle at the end of their life cycle – without a negative impact on the environment or humans. [17]

Phoenix Contact is implementing this principle in the expansion of its main site through the "Building 60" project, in which Cradle to Cradle certified products and modules are installed: glass partition walls, acoustic panels, windows and facades, among others, that are certified concerning material health, clean air and climate protection, responsible use of soil and water, social justice, and recyclability can thus restart the greenfield life cycle of a factory. [18]

This section’s factory life cycle model provides a holistic view of all characteristic time points during the lifespan of a factory. By distinguishing between a greenfield phase, an inner brownfield life cycle, and an end of life phase, factories from any phase can be described without needing a fixed starting point. At the same time, the complexity is kept to a minimum by tailoring the number of life cycle phases with the goal of the contribution, which is to create green factories that are as long-lasting and resource-efficient as possible. This goal can be achieved by going through the brownfield life cycle as often as possible: If companies can reuse production facilities repeatedly through upgrades, new CO_2 emissions or expenses are avoided, and the initial efforts of greenfield realisation can be relativised.

3.2 Upgrade and transformation of existing factories

Brownfield factory upgrades currently represent the most frequent planning case. Extending the lifespan of existing factory buildings through upgrades realises comprehensive ecological and economic benefits since, in addition to savings in CO_2 emissions, for example, sealing new areas is avoided or existing building structures can be cost-effectively reused. The initial expenses for construction and the energy bound in the building structures do not need to be incurred again. In addition, due to the politically envisaged net-zero land consumption target in Germany by 2050, future greenfield projects will be possible only in fewer numbers or with more elaborate compensatory measures. [19] This emphasises the necessity and importance of upgrade planning in the brownfield factory life cycle.

Generally, factory upgrades involve modernising or rebuilding the factory to improve or expand production. This can affect replacing production facilities, introducing new process technologies, energy renovation measures, or building expansion. In the interest of a consistent orientation towards climate-neutral net-zero factories, upgrades or repurposing should already be considered during the planning phase of the factory life cycle outlined in section 3.1 so that the factory can undergo the brownfield life cycle as long and as frequently as possible (see Figure 8). Generally, brownfield projects are significantly more complex to plan and realise due to existing restrictions on land and buildings. [19] Accordingly, forward-looking greenfield planning can greatly simplify factory upgrades in later brownfield cycles.

When sustainability aspects are comprehensively considered for the first time during the re-planning of an existing factory, this re-planning is not only an upgrade but also a transformation towards a climate-neutral green factory. This brownfield transformation process consists of several stages. In the beginning, the existing structures, energy and material flows, and emissions of the factory are analysed. Based on this data, initial areas for transformation can be identified. The definition of specific objectives results from analysing the market situation and forecasting future developments, e.g., using technology foresight or technology impact assessment. Projections for technological advancements and funding potential for technologies can be considered. In addition, the company strategy regarding future developments must be considered in this context. [19] The objectives for a sustainable factory can result, for example, from social, economic, and environmental challenges and opportunities through digitisation [20].

Following the definition of objectives for the transformation, implementation measures need to be identified and prioritised. BURGGRÄF ET AL. identify and define transformation measures concerning different factory levels in their Green Factory framework. Furthermore, a distinction is made between the fields of technology, materials and media, as well as organisation. This structuring makes it possible to identify measures for a specific planning case. Examples of possible actions include the use of photovoltaic systems, the use of sustainable materials, and the improvement of data quality. The conscious use of energy storage and avoiding (multiple) energy conversions, e.g., by using self-generated renewable direct current, are also desirable. [21] Even simple solutions such as green roofs can have several positive effects. In addition to the absorption and conversion of CO_2 and NO_2, significant advantages can be seen in insulation, resulting in reduced heating and cooling loads. When weighing the measures, the aim is to identify those with the most significant or cost-effective impact. [19] The DGNB certification program, e.g., uses a point system to prioritise measures [22].

By completing the actual transformation and thus the upgrade and realisation phase, a PDCA cycle (Plan-Do-Check-Act) or a CIP (Continuous Improvement Process) should be established as part of the subsequent operational phase. [19] This ensures that measures to achieve goals are sustainable and based on current standards. The operating phase can thus potentially be extended, and the need for re-planning can be reduced.

The practical implementation of such re-planning, upgrade, or transformation processes can be demonstrated through the examples of the companies Phoenix Contact and Lorenz. Phoenix Contact has set the strategic goal of a CO_2-neutral value chain by 2030. This strategy includes increasing energy efficiency by 25 %, achieving complete supply through renewable energy sources, and increasing the proportion of renewable energy self-generation to more than 30 %. In addition, by 2030, Phoenix Contact aims to be able to offset all remaining CO_2 emissions.

To achieve these goals at the production site in Bad Pyrmont, its sustainability-related transformation is necessary. In line with an All-Electric Society, a focus was placed on electrification. Phoenix Contact has identified areas central to achieving the transformation goals, such as the vehicle fleet, the combined heat and power plant, photovoltaic self-generation, or material delivery.

Measures derived from the analysis of the status quo include a nearly complete transition from combined heat and power plants to heat pumps for supplying the production site. Security of supply security is ensured by a remaining combined heat and power plant that operates on non-fossil fuels. This allows for decarbonisation by 2027 and limits price volatility risk by reducing natural gas and biomethane use. However, electrification and the switch to heat pumps also require a new energy supply concept in the buildings, which is based, among other things, on energy storage in the form of an ice storage system.

An ice storage system (see Figure 9) is a thermal energy storage system based on energy storage in the form of ice. This so-called latent heat storage is mainly used in conjunction with heat pumps to improve the energy efficiency of buildings. The system consists of a storage tank filled with water. During the winter, energy is extracted from the ice storage using a heat pump, causing the fluid in the ice storage to freeze. The crystallisation energy released during the phase transition can then be used to heat the building. The ice storage tank absorbs energy from the approximately 7 °C to 12 °C warm soil into which it is buried: the ice melts. This process is particularly fast on sunny winter days when sufficient energy is available from solar thermal energy and the heat pump extracts less or no energy from the ice storage. In the summer, the ice in the system is thawed again to store energy for the winter. The energy required for this process is extracted from the premises using the heat pump to cool them. In the interim season, when the heating or cooling demand is not as high as in winter or summer, the ice storage optimises the heat pump operation. The heat pump then uses the energy stored in the ice storage to increase or decrease the heating or cooling power, reducing the energy demand of the heat pump. In this way, the ice storage can serve as heat storage and increase the heat pump's efficiency, as the pump only operates when needed and does not have to be in continuous operation. [23]–[25]

In addition, Phoenix Contact intends to expand its photovoltaic self-production of electric-ity (see Figure 9). This allows for redundancy in connection to the power grid and the potential sale of excess energy. Transport losses, in particular, should be minimised to increase energy efficiency. Therefore, Phoenix Contact seeks synergies with public utility companies, farmers, wastewater treatment plants, or other local initiatives. For example, these entities are expected to supply the required biogas.

Expansion of Photovoltaic Systems

Ice Storage System for Energy Management

Figure 9: Measures taken by Phoenix Contact to transform the Bad Pyrmont site

The transformation of the Bad Pyrmont site towards renewable energies also leads to an increase in the complexity of the supply. To master this and enable future data-based decisions, comprehensive digitisation of the building is necessary. At Phoenix Contact, this has been implemented with the "Smart Building" initiative. The self-developed building management software *Emalytics*, also distributed to Phoenix Contact customers, visualises and tracks various building data. Only where all trades on site and functional areas communicate transparently and continuously with each other can energy be saved and future-proof automation be achieved. The IoT-based framework behind Emalytics enables this through the intelligent networking of all systems, equipment and components of MEP (mechanical, electrical and plumbing).

The Smart Building approach considers the entire life cycle of the building and plans the factory integrally. This serves not only to conserve resources, the environment, and human health but also to meet economic and human needs. The so-called peak shaving can be given as an example. At Phoenix Contact, during the start-up of energy-intensive equipment (e.g. soldering systems, injection moulding, etc.), building air conditioning is temporarily switched off to regulate energy consumption to less than 2.2 MW. This can achieve cost savings through peak load management, as an increased supply price must be paid for electricity consumption above the agreed quota of 2.2 MW. Networking in the Smart Building approach enables automatic sun protection control, providing employees with a more pleasant working atmosphere. Specifically, the Smart Building approach affects energy consumption in production: Since the introduction of the building management software in 2019, productivity has increased by 30 % (until 2022), while energy consumption has increased by only 6 %. The Smart Building approach supports an energy-conscious mentality of employees through the transparent display of energy consumption and increases motivation for self-responsible energy savings.

The transformation increases the sustainability of the Bad Pyrmont site, provides increased independence and redundancy from the power grid, and is economically feasible. Due to the change to heat pumps and the general growth of the site in production and development, Phoenix Contact predicts an increase in electricity demand of 10 % to 20 % by 2030. This demand increase is to be fully compensated for by an increase in energy efficiency. 30 % of the transformation investments are replacement investments, e.g., replacing a gas-fired boiler with an electric one. This shows that a large part of the investment costs for ecological transformation can be lowered by choosing a favourable procurement time – provided that building management and maintenance are closely synchronised with the company's strategic environmental goals. In addition, a one-time investment of approximately 5 million euros until 2030 is necessary for, among others, the expansion of the photovoltaic system and the changes in the heating and cooling concept. In addition, to ensure the security of supply, an investment in a photovoltaic park or a wind farm in cooperation with, for example, public utility companies is necessary.

The savings in operating costs exceed the projected investment costs in the long term. The site's transformation decreases operating costs despite the increasing energy demand. Based on the cost per kilowatt-hour in March 2023, this can be derived as follows: For self-generation through photovoltaic and wind power plants, the costs are significantly lower at 4 to 8 cents per kilowatt-hour than the procurement costs of coal or nuclear power, approximately 30 to 40 cents. Phoenix Contact, based on this, predicts no long-term challenges regarding the operating costs of the transformed site but instead regarding the security of supply. The company addresses this challenge by ensuring resilience and security of supply through local energy generation and system redundancy.

Also, Lorenz GmbH & Co.KG is striving to maximise the brownfield lifespan of its factory in a resource-efficient manner. The company's renewable energy generation achieves this by reducing production emissions. Among other things, Lorenz has a photovoltaic system with 573 kWp and expects approval to construct a small wind turbine with 24 kWp. Combined with a storage system with 490 kWh capacity (based on used vehicle batteries to avoid additional adverse environmental effects), which will be operational from August 2023, environmentally friendly electricity generation with high autonomy is achieved. The waste heat of a biogas plant located 500 meters away via a specially laid district heating pipeline covers heating energy almost entirely. Only in a few yearly weeks of frost is additional heating provided by a 100 kW log wood burner, with the firewood coming directly from farmers in the surrounding forests. Lorenz produces both new and refurbished products, the latter through an Upgrade Re-Assembly process. Therefore, shifts in the product portfolio are repeatedly observed. At times, more new than refurbished products are produced. After the end of the first usage cycle of new products, there is a shift towards the refurbishment. Necessary changes to the production lines and logistics areas (for example, through the required cleaning or increased space requirements for intermediate storage of incoming used parts) were only quickly feasible through a modular building concept with movable walls and removable facade parts. This underlines the importance of considering and enabling foreseeable changes and upgrade requirements for the brownfield life cycle already as part of greenfield planning.

This section presented potentials and possible implementations for upgrading, re-planning, and transforming factories. Using the example of Phoenix Contact, it was shown that sustainability-related transformation, such as in the area of energy supply and efficiency, can reduce the operating costs of a site in the long term. However, the potentials of factory transformation go beyond purely financial aspects. For example, Phoenix Contact creates redundancies in supply through its electricity production, thereby increasing the security of supply. With Lorenz, the flexibility of production with regard to necessary re-planning in the foreseeable future has already been increased through greenfield planning with a modular building concept.

A study by BURGGRÄF ET AL. among 45 decision-makers for factory planning projects shows that brownfield projects are considered risky. 38 % of the study participants consider such projects aimed at re-planning existing factories as rather risky or highly risky. [26] This risk assessment carries the danger that upgrade or transformation processes – and thus necessary investments for implementing a circular economy – will be hindered or slowed down. Therefore, measures are required to reduce the risk of upgrading and transforming factories. Transparent data collection, especially building operational data, can contribute to this. Challenges regarding innovations and changes in the brownfield cycle are thus precisely reflected and analysed through digital planning tools [27]. Only in this way can the appropriate adjustments towards an efficient and climate-neutral building and production operation be identified.

3.3 Building Information Modeling (BIM) to enable the Green Factory

The transformation process from conventional factories to climate-neutral Green Factories outlined in section 3.2 poses special requirements for planning. For resource-efficient but increasingly complex building technology to reliably meet the production requirements for the desired long factory lifespans, close collaboration between all trades on site is necessary, particularly between production and MEP. Thus, the sustainable transformation of existing factories reinforces already observable trends in planning: the traditional and multidisciplinary construction process is becoming increasingly complex [28] and, therefore, more costly by integrating additional interfaces. BIM enables the necessary data consistency and efficiency in planning and implementation to manage the increasing planning complexity. When BIM models are combined with building management systems, the potential for building operation can also be realised.

BIM is a method that enables the systematic, detailed, and cooperative creation of three-dimensional digital models of buildings. An exact structure representation is created and continuously supplemented through the digitisation of planning, construction, and operation (administration, maintenance, facility management, etc.). [29]–[31] The digital and three-dimensional (geometric) building model represents only part of the BI model in BIM. It is successively created and filled with data or semantic information by all involved planners and trades in all life cycle phases. Semantic information is considered an attribute of objects in the BI model and can indicate, for example, the fire protection class, energy consumption, or price of a system. This ensures consistency in communication and data exchange between all those involved in planning and execution. [29], [30] The BI model can include temporal, logistical, and commercial aspects.

BIM shifts planning efforts to early planning phases through the early creation of the digital building model. Content or geometric checks can detect and avoid planning errors early. This can prevent unexpected add-ons and cost increases, leading to higher cost security and schedule adherence. [30], [32] Such savings in costs and time are associated with resource savings. In addition to the advantages of BIM that mainly apply to planning, re-planning, transformation, upgrade, and the realisation of buildings, there are also advantages that can be used during the operation of Green Factories.

In terms of resource-efficient and durable production buildings, BIM can be used to improve the energy design of the building and enable a more efficient [12] and, therefore, environmentally friendly building operation. Energy-efficient building requires various partially complex measures that are difficult to manage with traditional planning and implementation methods. In addition, it is conceivable to examine or simulate in the digital BI model at an early stage how different planning variants of the building and production contribute to sustainability goals. This allows the most advantageous variant to be selected and further optimised. Although some simulation tools are already available, one is yet to cover the entire building life cycle [33].

Thus, BIM can be used for the Green Factory to master complexity and obtain valid planning results as time-efficiently as possible and without rework. In summary, BIM enables the integration and resource optimisation of all phases of the factory life cycle, from planning, realisation, operation, re-planning, and dismantling [12]. Thus, retroactively creating a BIM model in existing structures can also be helpful, for example, before a transfor-mation process, as cross-life-cycle benefits arise.

Phoenix Contact is also planning a new building at the Blomberg site (see Figure 10) with BIM, aiming for maximum energy efficiency. Various measures will be implemented, such as modern energy and climate technology, a photovoltaic system with more than 1.5 MWp, or intelligent energy management and automation solutions [34].

Phoenix Contact is using BIM not only for the new planning at the Blomberg site but also for transforming existing buildings at the Bad Pyrmont site. The existing facilities in Bad Pyrmont were initially planned without BIM. Subsequently, a BIM model was created for the transformation process, with which the planning and implementation process is cur-rently being carried out, for example, in the form of HVAC (heating, ventilation, and air conditioning) and electrical planning.

In addition to the new planning in Blomberg and the transformation in Bad Pyrmont, BIM can also be used to operate Phoenix Contact's factory buildings. If the comparatively high and long-lasting energy consumption in the operation phase is optimised, significant po-tentials can be realised on the way to a climate-neutral Green Factory [33]. The BIM model is used as a starting point for Emalytics. For this purpose, older systems without data interfaces are retrofitted with *data collection boxes* to integrate them into the digital twin. In addition, the software is used in networking production systems and technical building automation for the already presented peak shaving (cf. section 3.2).

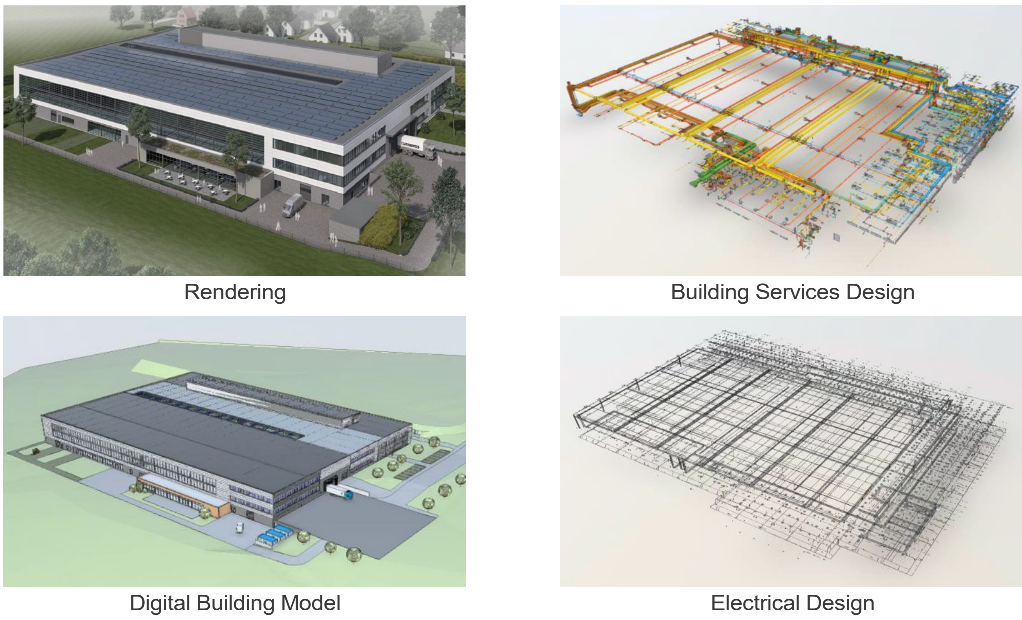

Figure 10: Greenfield BIM planning of a building at Phoenix Contact's Blomberg location

It has been shown that using BIM results in a more efficient planning, construction, oper-ation, re-planning, and dismantling process. In addition to these "traditional" aspects, BIM can also be used to achieve goals in green factories, such as resource efficiency optimi-sation and building lifespan extension, as outlined in the factory life cycle model from section 3. For example, the complex energy-efficient planning of buildings can be man-aged through BIM. Furthermore, investigations on how planning alternatives contribute to sustainability goals are already possible within the BIM model. During the operation of the Building, BIM can contribute to optimisation by making the building model and all data accessible to other software solutions. For instance, in the future, peak shaving in Emalytics could be further developed to perform energy-intensive tasks when renewable energy (such as from own solar panels) is available to achieve minimal CO_2 emissions and electricity costs.

Moreover, the example of Phoenix Contact demonstrates that BIM is also useful for the increasingly relevant brownfield (cf. section 3.2) – both in the transformation of an existing building (Bad Pyrmont) and as input for a digital twin (building automation or peak shaving). Furthermore, new requirements arise for a factory building that should be operated as long and resource-efficiently as possible, which deviate from traditional requirements. BIM leverages its advantages here, as integrating building models from different stakeholders can support the sector coupling necessary for an All-Electric Society. Complex requirements can be processed in a transparent digital building model time- and cost-efficiently throughout the entire lifespan of the building. Specifically, BIM can support factory buildings that must meet the requirements of changing products and product conditions throughout their life cycle. BIM can locate the Upgrade Re-assembly processes outlined in section 2 in long-lasting and resource-efficient Green Factories.

4 Conclusion: The Green Upgrade Re-Assembly Factory enables sustainable production and is profitable

The Green Upgrade Re-Assembly Factory (Figure 11) demonstrates the necessary design of a new type of factory, simultaneously laying the operational foundations for value- and function-enhancing circular economies and enabling production with an ecologically minimal footprint.

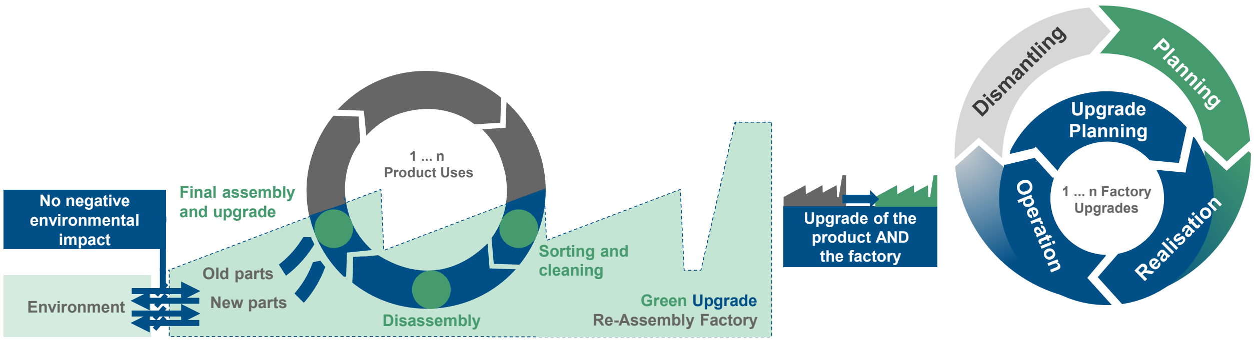

Figure 11: Green Upgrade Re-Assembly Factory

Prominent industrial examples have demonstrated that both the value- and function-enhancing closed-loop circulation of products through life-prolonging measures, as well as the ecological transformation of factories, can be realised in an economically profitable manner.

The comprehensive implementation of sustainable production offers a decisive competitive advantage over conventional production methods in a dual sense: the necessary transformation from a linear to a circular economy can be achieved while increasing the profitability of individual companies.

For sustainable production, it is essential to repeatedly adapt the product and the factory to changing market requirements. The upgrade in the presented concept of the Green

Upgrade Re-Assembly Factory is, therefore, to be understood concerning the product and the factory. New product and factory life cycle models consider this.

The article shows that a Green Upgrade Re-Assembly Factory is profitable for companies – even without intensification of government support or increasing industry sustainability requirements. If, as expected, there is an intensification of government incentives in the coming years, such as subsidies or increasing taxation of CO_2 equivalents, the profitability of sustainable production will increase. Thus, in the future, companies that have already aligned their strategy towards sustainable transformation will benefit in particular.

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4.3 New Quality Paradigm for Sustainable Production

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Abstract

New Quality Paradigm for Sustainable Production

Due to their embedding in complex social systems, manufacturing companies are exposed to multiple demands from different interest groups or stakeholders, which make it necessary to give greater weight to ESG- (Environmental Social & Governance) than to financial-economic criteria. To be able to meet these demands in a future-oriented manner, these ESG aspects must be considered within the strategy and decision-making processes and integrated into the entirety of all value creation activities of the companies. This paper shows how the apparent increase in the diversity of market demands on companies due to sustainability aspects can be managed and seized as an opportunity. To this end, different perspectives of corporate action are illustrated, and potentials are pointed out as to how companies can orient their activities from within towards an ESG- and at the same time quality-oriented, economically viable target image. To highlight this, a concrete company example is presented. In this context, quality management with its process- and KPI-oriented as well as cross-functional character offers the ideal prerequisites for proactively supporting this transformation. In addition to the proven capabilities and mechanisms, there is a need for Q*uality Management* itself to react proactively to changing framework conditions and to transform itself in the direction of *"Quality Intelligence"*.

Keywords: Quality Management, Sustainability, Requirement Engineering, Transformation

Kurzfassung

Neues Qualitätsparadigma für die nachhaltige Produktion

Aufgrund der Einbettung produzierender Unternehmen in komplexe Gesellschaftssysteme sehen sich diese einer Vielzahl an Forderungen unterschiedlicher Interessengruppen ausgesetzt, die insbesondere eine stärkere Gewichtung der ESG- (Environmental Social & Governance) gegenüber den finanziell-ökonomischen F-Kriterien notwendig machen. Um diesen zukunftsgerichtet begegnen zu können, müssen ESG-Aspekte innerhalb der Strategie- und Entscheidungsfindungsprozesse berücksichtigt und von Grund auf in alle Wertschöpfungsaktivitäten der Unternehmen integriert werden. Innerhalb dieses Beitrags wird aufgezeigt, wie die scheinbare Zunahme der Vielfalt marktseitiger Anforderungen von Unternehmen aufgrund von Nachhaltigkeitsaspekten bewältigt und als Chance ergriffen werden kann. Hierzu werden verschiedene Perspektiven des unternehmerischen Handelns beleuchtet und Potenziale offengelegt, wie Unternehmen ihre Aktivitäten von innen heraus auf ein ESG- und zugleich qualitätsorientiertes, wirtschaftlich tragfähiges Zielbild ausrichten können. Zur Veranschaulichung wird ein konkretes Unternehmensbeispiel vorgestellt. In diesem Kontext bietet das Qualitätsmanagement mit seinem prozess- und kennzahlenorientierten sowie funktionsübergreifenden Charakter die idealen Voraussetzungen für die proaktive Unterstützung dieser Transformation. Zusätz-

lich zu den bewährten Fähigkeiten und Mechanismen besteht für das Qualitätsmanagement selbst die Notwendigkeit, proaktiv auf sich wandelnde Rahmenbedingungen zu reagieren und sich in Richtung einer „Quality Intelligence“ weiterzuentwickeln.

Schlagwörter: Qualitätsmanagement, Nachhaltigkeit, Anforderungsmanagement, Transformation

1 Introduction

Manufacturing companies are increasingly confronted with challenges regarding energy supply, the monitoring of global supply chains, and the responsible use of limited resources. The resulting uncertainties are exacerbated by economic and political disruptions, and the already perceptible consequences of climate change [1].

Within this volatile and crises-ridden economic environment, sustainability is becoming an important priority [2]. Since the adoption of the Paris Climate Agreement in 2015 and the compromise of reducing the global average temperature increase to below 1.5°C compared to pre-industrial values, legal requirements have changed the framework conditions for businesses practices [2], [3]. For instance, the CSR Directive Implementation Act (CSR-RUG) was passed in 2017, mandating that capital-oriented firms with over 500 employees must address environmental, social, employee concerns, human rights, and the fight against corruption and bribery in their management reports. [4] The Supply Chain Due Diligence Act (LkSG), which went into effect this year, focuses on ensuring companies' compliance with human rights protection in global supply chains [5]. Moreover, the Corporate Sustainability Reporting Directive (CSRD) is currently being implemented, which gradually imposes the obligation of sustainability reporting for European companies. The directive requires companies to report on the impact of their sustainability efforts on their business performance and business development, as well as on the impact of these efforts on people and the environment. [6] Based on present trends, more regulations are likely to come in the future, concerning compliance and disclosure of sustainability aspects and key figures. The resulting requirements, combined with the existing challenges, will lead to an increased complexity for the strategic and operational orientation of manufacturing companies.

As companies operate within social systems it is necessary to consider further sustainability-oriented demands from external interest groups in addition to legal requirements [7]. The mutual interactions with different interest groups are subject to constant change [8]. For instance, it can be observed that more and more consumers are developing an increasing environmental awareness, so that sustainability is emerging as a relevant competitive factor. Surveys show that 48% of consumers are willing to accept a higher offer price for more sustainable products [9]. At the same time, sustainability can act as an innovation driver by proactively considering new requirements in the context of product and service development. Additional factors to consider are the changed requirements for securing human and financial resources due to the attractiveness of a company for the labour and financial markets. [7].

An essential prerequisite for the long-term success of companies is not only the flexibility and adaptability of their organization to changing conditions, but also the adaptation and positioning of products according to changing customer needs. To secure a long-term stable market position, an essential competitive factor is to recognize changes at an early stage, to create new markets, and to awaken customer needs. [10] At the same time, companies need to operate with the aim of increasing profits in the long term while permanently securing liquidity [11]. The additional sustainability requirements in terms of environmental, social, and governance (ESG) criteria require a change in how companies are managed to efficiently solve this conundrum. [2]

The arguments given demonstrate that meeting market requirements has become a challenging and multi-faceted task for companies. Consequently, standardized mechanisms are necessary to identifying and evaluating key stakeholders, as well as considering their requirements when developing business targets and strategies. The adoption of normative company guidelines also requires a corresponding implementation of sustainability principles throughout the organization. Due to its structurally interdisciplinary and cross-functional character, quality management has the potential to decisively enable a sustainability-oriented transformation. The organizational and technical challenges for quality management lie in proactively responding to changing conditions while leaving behind its historically normative-conservative role. This article will explain how companies can handle the variety of market requirements and see the transformation of quality management as an opportunity.

2 Paradigm Shift for Quality-oriented Companies

Against the background of the development of today's quality management, the necessity and topicality of a new paradigm becomes clear. Requirements of industrial practice and their effects shape today's quality management. Due to the increasing importance of sustainability for manufacturing companies, current movements thus influence the now inevitable paradigm shift.

2.1 Historical Quality Paradigms of Manufacturing Companies

The evolution of quality management has always been closely tied to the continually changing environment of manufacturing companies. This is exemplified by the first industrial revolution, which occurred in the late 18th century and led to the mechanization of production. [10], [12] The shift towards mass and assembly line production demanded a change in quality thinking, given the alterations in the working conditions compared to make-to-order production.

However, during this time, product inspection was limited to the detection and removal of defective components [10]. In the 1920s, the use of statistical methods for quality control meant that complete testing was no longer necessary. Hence, it enabled the targeted control of processes and the resulting reduction in the volume of rejected products. This laid the foundation for the change from a purely reactive (quality control) to a proactive quality approach (quality assurance). [13], [14]

At the beginning of the 1950s, defect costs became increasingly important as a control and management metric. In 1956, the Total Quality Control (TQC) approach was developed based on the idea that failures in the early stages of product development lead to high costs later on. [10].

Parallel to these movements, which took place primarily in the USA, a radical turnaround was initiated in Japan toward the targeted orientation of production to market requirements. A systematic procedure was developed for the continuous optimization of processes, which is still known as the Deming cycle or Plan-Do-Check-Act cycle (PDCA) and continues to be a standard tool in many companies. [13] The PDCA cycle also forms the basis for many current management systems. [10]

In the mid-1980s, the term Total Quality Management (TQM) shaped the understanding of a holistic quality management concept. [15] TQM understands quality as the task of all areas and employees in the company, as well as a philosophy of the entire organization [16]. At the same time, Motorola started the initiative to improve customer satisfaction by developing the Six Sigma method with the underlying systematic approach *Define-Measure-Analyze-Improve-Control* (DMAIC). [10], [16] The International Organization for Standardization (ISO) introduced a further holistic quality management concept in 1987 with the publication of DIN ISO 9000ff, referred since 2000 to as "Quality management systems requirements”. [10], [13] A major contribution of this standard is the most widely recognized definition of quality as "the degree to which a set of inherent characteristics meets requirements" [17]. This definition emphasizes the need to consider market requirements in the context of product and service provision.

In 2011, the term "Industry 4.0" was presented to the public for the first time as the German government's vision for the German industry [14]. After the steam engine (1.), mass and assembly line production (2.) and the introduction of computer-aided controls and robots (3.), the fourth great leap to increase productivity was initiated with the "Internet of Things" and the implementation of cyber-physical systems [18]. The vertical linking of embedded systems with production and business processes and their horizontal networking to form distributed value-added networks that can be controlled in real-time create new challenges and potentials for quality management. This particularly applies to data quality, processing, and assurance [10], [18].

In addition to the technological focus of Industry 4.0, topics such as sustainability, resilience, and human-centeredness are entering the focus of attention of companies and consequently triggering a renewed development of quality [19]. It requires the balancing of economic, ecological and social effects and interactions. The change in the understanding of sustainability underlines its relevance today.

The oldest use of the term sustainability in the German-speaking area dates to the year 1713. In the treatise "Sylvicultura Oeconomica", a "continuous, constant and sustained use" of the forest was demanded to adjust for deforestation according to the limits of reforestation. [20], [21] It was not until 1953, with the publication of the "Social Responsibilities of the Businessman", that a company's social obligations towards society moved into the discourse. The publication states that companies have a responsibility to consider the impact of their actions on all stakeholders, including employees, customers, and the wider community. [22], [23]

The scientific presence of sustainability began with the study "Limits of Growth" commissioned by the Club of Rome in 1972. [24], [25] The analysis postulated that unlimited growth is not possible and would inevitably lead to the system's collapse [25]. In the publication of "Our Common Future" in 1987, the World Commission on Environment and Development report states the understanding of sustainable development as satisfying the needs of the present generation without compromising the needs of future generations. Furthermore, the report distinguishes the sustainability dimensions environment, economy, and social. [20], [27]

In addition to the financial and economic indicators (F-criteria), the definition of the three pillars of sustainable business (ESG criteria) was officially introduced in 2004 by the United Nations Global Compact Initiative in the "Who Cares Wins" report. Environmental (E) covers climate and environmental protection issues. For instance, a company's efforts in relation to greenhouse gas emissions reduction and environmental management are assessed under this criterium. Social (S) considers aspects of human rights, social stability, and occupational health and safety legislation, among other things. Governance (G) includes aspects that assess internal processes and responsibilities, such as control procedures, anti-competitive practices, and compliance with laws. [28], [29]

The development of the 17 "Sustainability Development Goals" (SDGs) from 2015 as part of the United Nations 2030 Agenda extended the significance of the three sustainability dimensions. The outcome document of the summit states, "They are integrated and indivisible and take into account in a balanced way the three dimensions of sustainable development: economic, societal, and environmental" [30]. With the formulation of the SDGs, the international community agreed for the first time on fields of action and an orientation framework for companies [31].

Society has also become aware that the path taken for dealing with limited resources cannot be continued. This is reinforced by the "World Overshoot Day" on July 28, 2022, after which natural regeneration will no longer be able to cover the annual consumption of biological resources. [32] Governments have created normative framework conditions for sustainability. However, it has become increasingly apparent that interest and stakeholder groups and their requirements must be taken into account, which have an influence on companies' actions and thus on their self-image (Figure 1).

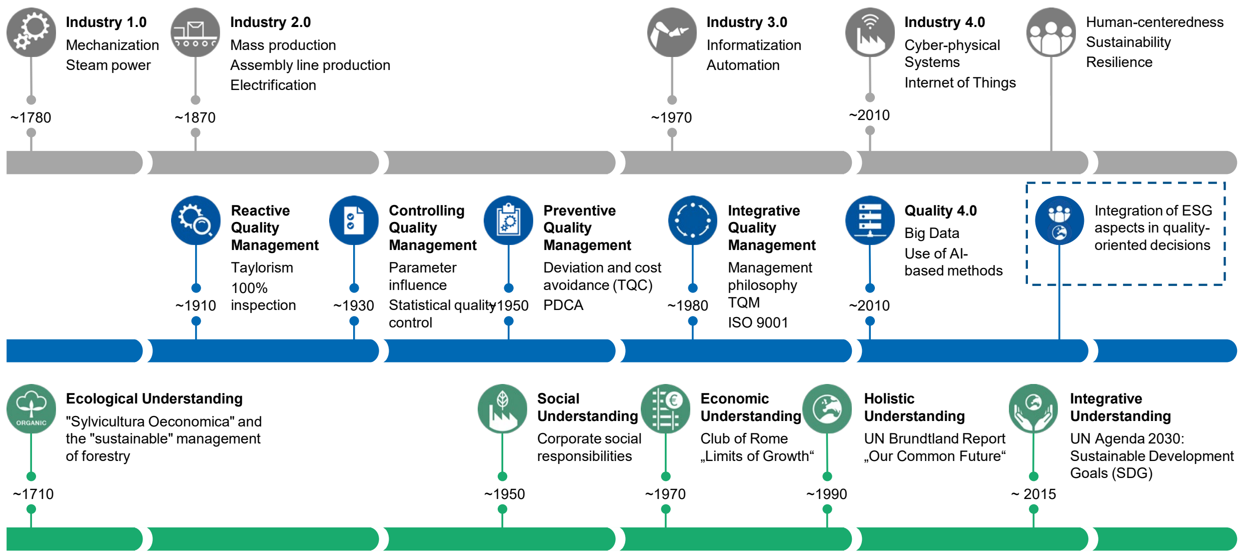

Figure 1: Paradigm development from the perspective of manufacturing companies [10]-[31]

2.2 Sustainability as Part of the New Quality Paradigm

The change in the understanding of quality and sustainability is characterized by high complexity and dynamics [10], [20]. Due to the steadily increasing importance of sustainability for manufacturing companies, an independent consideration is not plausible. Rather, both aspects complement each other in the sense of a holistic, continuous optimization. This inevitably means that the understanding of quality faces the next transformation: Expanding quality awareness by including the sustainability perspective. For a modern definition of quality, the demand is stated to consider an overall societal balance [31]. In order to realize this, a transformation in line with the changing requirements must be implemented. This concerns the organization in its entirety and, thus, all facets of quality management.

The systematic transformation of organizational structures requires a suitable regulatory framework. Established, integrated management systems provide a promising approach. Particularly in quality-oriented companies, management systems are structured according to the High-Level Structure of the ISO standards, which include basic definitions and requirements such as in the DIN EN ISO 9000 series [17]. This standardization promotes synergies and reduces both implementation barriers and redundancies. [8] For the implementation in a company environment, the “Aachener Quality Management Model” (ACQMM) was developed in compatibility with the requirements of DIN EN ISO 9001 (see Figure 2). The model aims to represent the quality-related tasks in a company from the perspectives of the market, business operations, and management. In doing so, the lifecycle-oriented ACQMM takes up the process-oriented approach of the management system standards. [10]

The resulting extended definition of quality for companies describes it as the "degree of overlap between market requirements (market perspective), company orientation (management perspective) and company capabilities (operational perspective)". [10] Market requirements play a crucial role in shaping the design of service provision, as they are addressed according to the company's focus and goals. The company orientation forms the framework of the company’s activities through the definition and specification of the vision, pursued strategies and goals. The company capabilities comprise existing tangible and intangible resources to produce services, for example in the form of operational resources and know-how.

Broadening the perspective of companies entails an expanded spectrum of requirements, which have implications for both the company's orientation and the design of the company's capabilities. [33] From the point of view of corporate alignment, these must be integrated into existing the strategy and goal-setting processes. In this context, it becomes clear that the company's management must initiate the development towards sustainability orientation. [2] This vision should be driven by the management as a prerequisite for enhancing the company's capabilities through the adoption new technologies and resources.

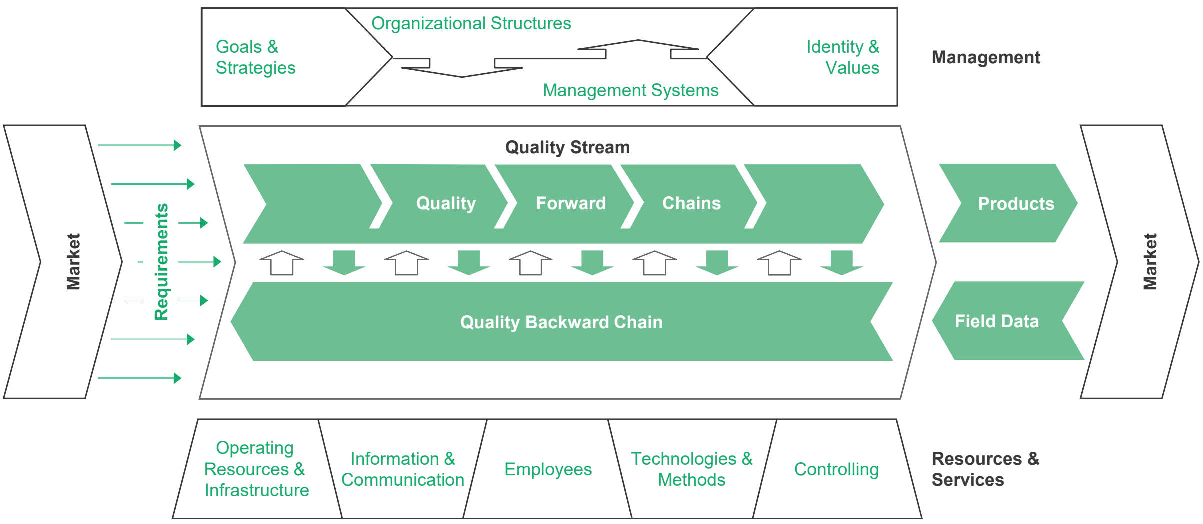

Figure 2: The sustainable realignment of a company's activities along the Aachen Quality Management Model [10]

Merely relying on management-led initiatives is insufficient to achieve a successful and effective transformation. Additional mechanisms and a responsible authority for implementation are required to enable a change across all levels. Considering a company’s competencies and its value system, quality management can take on the role of leading the organizational change towards quality and sustainability orientation. [34]. To achieve this, it is crucial to emphasize methodological competencies in data acquisition, processing and analysis, and to derive optimization measures accordingly. The cross-functional and interdisciplinary nature of quality management provides the basis for fulfilling this task. Moreover, the existing principles and mechanisms of quality management must be critically assessed. The inclusion of sustainability aspects and a combined targeted methodical and technological transformation offer companies new development options.

3 Analysis of the Paradigm Shift from the Perspectives of the Aachen Quality Management Model (ACQMM)

The transformation along the three perspectives of the ACQMM includes possible levers for manufacturing companies to create a sustainability-oriented organization. The theoretical explanations are complemented by the concrete use case of a company whose challenge is to create transparency regarding its carbon footprint and to prepare mechanisms to comply with the new regulations of the German Supply Chain Compliance Act (Lieferkettensorgfaltspflichtengesetz, LkSG). The Sigreen software from Siemens AG [35] illustrates a possible technology-based solution approach to the case at hand, which enables the exchange of supply chain data according to the latest regulations and security standards.

3.1 Market Perspective

According to the quality understanding underlying the ACQMM, the market is the starting point for all quality-related activities. The market is understood as the union of "all heterogeneous, diversified and temporarily changing groups that are interested in the successful performance of the company". Thus, the market includes not only external customers, but also internal stakeholders, suppliers, shareholders and other interested parties. [10] The market perspective described in the ACQMM can therefore be seen as a broader definition of the company’s business environment, encompassing all interest groups of the company. The composition of these interest groups sometimes leads to contradictory requirements to be fulfilled by the company management.

The identification of stakeholders is useful for the orientation of the company and corresponds to the requirements of the ISO 9001 for an organization. The norm requires to identify the relevant stakeholders and to describe their requirements regarding the company’s management system. Especially by expanding the company’s scope with regards to sustainability, new interest groups or stakeholders are included. For the purpose of this paper, relevant stakeholders, which directly or indirectly influence business activities or have direct or indirect sustainability requirements on a company, were identified and discussed by the expert panel involved. The stakeholders include the labour market and employees, shareholders (owners, partners, and investors), financial market, society, customers, government, and regulatory bodies. [7], [36]

The growing importance of sustainability has an impact on the labour market and influences personal decisions in professional life. Companies that lead the way with sustainable business practices could have an easier time attracting well-trained employees in a competitive market. [2] Another important aspect is the increasing importance of sustainability for investors. Banks and financial market companies are also placing increasing emphasis on sustainability in their investment portfolios. Companies that require capital from the financial markets can obtain better conditions in the long term by operating sustainably. One example is the EU regulation to facilitate sustainable investments, which sets a framework for classifying investments, thereby creating transparency in the financial markets. [37]

Against the background of a broadened spectrum of requirements, the analysis of re-relevant standards and guidelines provides a starting point for the verification of the identified stakeholders. Over time, several initiatives have been developed to support companies in implementing sustainability-oriented systems and consider already a wide range of requirements. These range from sustainability reports to certifiable guidelines and management systems to legal regulations. Legal requirements for sustainability reporting include the CSR-RUG, the recently enacted LkSG and the CSRD initiative. In addition, guidelines compatible with the quality management standard DIN EN ISO 9001, such as DIN EN ISO 26000 for corporate responsibility [38], DIN EN ISO 50001 for energy management systems [39], or DIN EN ISO 14001 for environmental management systems [40], can support the development of integrated management systems. Similar to the LkSG, the SA8000 standard provides a recommendatory reference regarding corporate responsibility to respect human rights in global supply chains [41]. The Global Reporting Initiative (GRI) [42], the UN Global Compact [43], the ZNU standard [44], the German Sustainability Code (DNK) [45] and the Common Good Economy (GWÖ) balance sheet [46] represent further guidelines for corporate reporting that can be linked to the SDGs. The Greenhouse Gas Protocol (GHG Protocol) differentiates the emissions of a supply chain in three areas and categorizes the causes so that targeted measures can be identified. [47] The variety of standards listed illustrates the evolution of requirements over time. The following Table 1 provides structured information on selected standards, certificates and reports and thus offers companies an initial guide as to which sustainability aspects are addressed by which of the identified standards and guidelines.

Integrated management systems based on a range of standards such as DIN EN ISO 9001, DIN EN ISO 14001, DIN EN ISO 26000 or DIN EN ISO 50001 already offer guidelines for designing structures that take into account the sustainability requirements of a broad spectrum of stakeholders. In addition to these guidelines, a targeted decision-making process and the efficient use of resources are required to meet current requirements. To reduce the complexity of the decision and associated resource allocation problem, the requirements of the relevant stakeholders must be articulated and prioritized. To exemplary illustrate this conundrum, a company may face a conflict of objectives between the environmental needs of its customers and the society, the safety requirements of its employees, the regulatory requirements of the government, and the financial needs of its shareholders.

Table 1: Overview of selected standards, certificates, and reports in the field of sustainability and the addressed stakeholders [17], [38]-[47]

	Type / (Certificate or Logo available)	Aspects	Addressed Stakeholders	Requirements	Scope	Compatibility
ISO 14001: Environmental Management Systems	Certifiable standard for environmental management systems (Yes)	EN	G, SO	8 thematic blocks, documentation and indicator proof (environmental indicators)	Annual surveillance audits, re-certification every 3 years	ISO 9001, ISO 50001
ISO 26000: Guidance on social responsibility	Corporate responsibility guide	EN, SO, EC	C, F, G, S, SO	7 core topic blocks		
ISO 50001: Energy Management Systems	Certifiable standard for energy management systems (Yes)	EN		8 Topic blocks, documentation and indicator proof (energy performance indicators)	Annual surveillance audits, re-certification every 3 years	ISO 9001, ISO 14001
SA 8000: Social Accountability International	Certifiable standard for working conditions (Yes)	SO	G, L, R, SO	8 thematic blocks, documentation	Semi-annual surveillance audits, re-certification every 3 years	ISO 9001, ISO 14001
GRI: Global Reporting Initiative	Reporting standard (Yes)	EN, SO, EC,	L, R	Extensive, detailed reporting on a wide range of topics (documentation and indicator evidence, varies by industry)	Establishment of a consistent reporting cycle by organization (usually annually)	DNK, ZNU
UN Global Compact	Commitment and rudimentary reporting standard (Yes)	EN, SO	L, SO	6 thematic blocks in questionnaire, statement of the management	Application for membership, followed by annual questionnaire and statement of the management	
ZNU-Standard	Certifiable standard for building an integrated management system (Yes)	EN, SO, EC	SO	32 thematic blocks, documentation and indicator proofs (environmental and energy key figures)	Annual surveillance audits, re-certification every 3 years	ISO 9001, ISO 14001, ISO 50001, SA 8000, GRI, DNK
DNK: Deutscher Nachhaltigkeits-Kodex (German Sustainability Codex)	Reporting standard (Yes)	EN, SO, EC	L, SO	20 topic blocks, documentation, evidence of indicators (non-financial performance indicators)	Annual reporting	GRI, CSR-RUG, ZNU
GWÖ: Gemeinwohl-Ökonomie (Economy for the Common Good)	Common good balance sheet and transparency standard (Yes)	EN, SO, EC	F, R, S	20 thematic blocks, documentation	Intensive participation in the organization for the GWÖ required	
Greenhouse Gas Protocol	Greenhouse gas emissions calculation standard	EN	C, F, L	18 aspects of greenhouse gas emissions across 3 scopes		

Aspects: EN = Environment; SO = Social; EC = Economic;

Stakeholders: C = Customers; G = Government & Authorities; F = Financial Market; L = Labor Market & Employees; R = Regulatory Bodies; S = Shareholders & Investors; SO = Society

To evaluate the requirements of the stakeholders, a classification approach based on the *Kano* model for evaluating the quality requirements of a product is developed. Departing from the *Kano* model, the characteristics of a product are divided into *Must-be quality* characteristics which must be fulfilled in order to be accepted by the market at all, *One-dimensional quality* characteristics which are explicitly demanded by the market and on the basis of which products are primarily compared, and *Attractive quality* characteristics which are not directly demanded by the market but have the greatest influence on market satisfaction when fulfilled. [10] Based on this, the simplified scale *must*, *should*, and *could* can be derived to classify the sustainability requirements of the market perspective. The *must* level places minimum requirements on a company as a prerequisite for operating in a market economy, such as meeting legal requirements and the interests of shareholders. The *should*-level places requirements on a company to secure its economic situation and profitability, such as meeting customer requirements and standards. Finally, meeting the requirements of the *could* level leads to companies being perceived as acting responsibly. These requirements are not explicitly expected by stakeholders and can be seen as growth drivers. The *Kano* model further states that *Attractive quality* become *One-dimensional quality* and finally *Must-be quality* characteristics over time. [10] In the expert panel involved in this paper, the following hypothesis was formulated: sustainability requirements develop from *could* requirements in the direction of *must* requirements over time. To exemplify this, longer existing requirements on sustainable management have been transformed into existing regulations such as the CSR-RUG and the LkSG [4], [5]. Like in the *Kano* model, the hypothesis does not state that all *could* requirements change over time into *should* requirements, but that a temporal principle generally underlies them. The proposed classification approach for stakeholder requirements from the market perspective is shown in Figure 3.

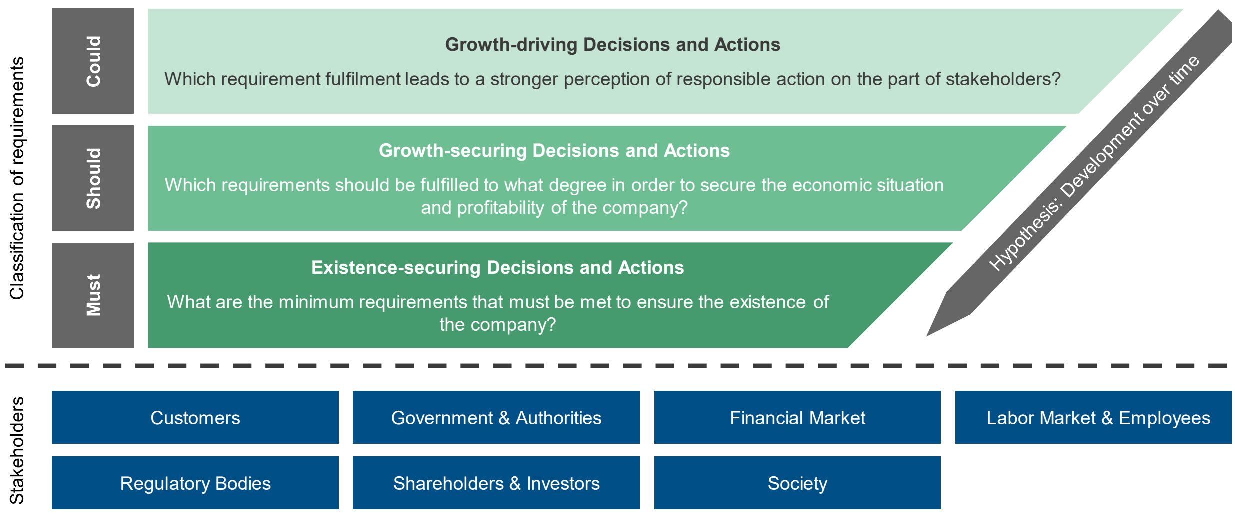

Figure 3: Classification approach for stakeholder requirements of the market perspective

Due to the partly contradictory demands of the stakeholders on the company, a management perspective as described in the ACQMM is necessary, which provides a prioritization of the stakeholders and thus their requirements by the company management.

3.2 Management Perspective

According to the ACQMM, the management perspective focuses on the system quality of a company to provide products and services that meet the requirements of the stakeholders [10]. The quality-oriented structures and the underlying management systems represent an important design field for this purpose. Sustainability requirements hence have an impact on the company's quality policy and objectives. To ensure that ESG-related activities are managed effectively and efficiently, they must be embedded in the strategic decision-making and goal-setting processes of the company's management. The company management acts as the initiator and driver of quality initiatives. A central function includes defining and exemplifying the company's values. Furthermore, strategy definition is an essential task to enable a successful consideration of market demands for the creation of inspiring products and services. This is not only about maintaining the current business status of the company, but also about securing its future competitiveness. [10] For the evaluation of the system quality of a company, an alignment with the changed quality perspective of the stakeholders is required.

Based on the normative quality definition according to DIN EN ISO 9000, meeting current requirements of the stakeholders would imply adding the combined ESG criteria. In order to include the economic efficiency principle of companies, requirements can be classified according to the degree to which the fulfilment ensures the economic growth success of the company. To determine the prioritization of requirements, a materiality matrix can be used. The analysis is based on the concept of dual materiality as set out in the proposals for the CRSD Directive. On the one hand, it includes the impact of sustainability aspects on the business result, business situation and business performance ("outside-in perspective"). On the other hand, the effects of business activities on people and the environment ("inside-out perspective") are analysed. [6] Here, the requirements relevant to the company are positioned along two axes: The impact on the company's business activities as the abscissa and the relevance for stakeholders as the ordinate. The matrix depicted in Figure 4 has been developed based on the requirements of the ZNU standard of the *Center for Sustainable Management* at the University of Witten / Herdecke. The ZNU standard is a practice-oriented and certifiable standard for sustainable management with the aim of making sustainability tangible and measurable for companies. The standard incorporates multiple standards, guidelines, and sets requirements for the management of companies regarding specific sustainability topics in the three dimensions of environmental, economic and social issues. Within the framework of the ZNU standard, a materiality matrix can be used as evidence for the systematic recording of the fields of action of a company in the sustainability areas. [44] Based on the classification model for stakeholder requirements presented in chapter 3.1, the matrix axes are divided into areas that qualitatively map the *must*, *should,* and *could* areas.

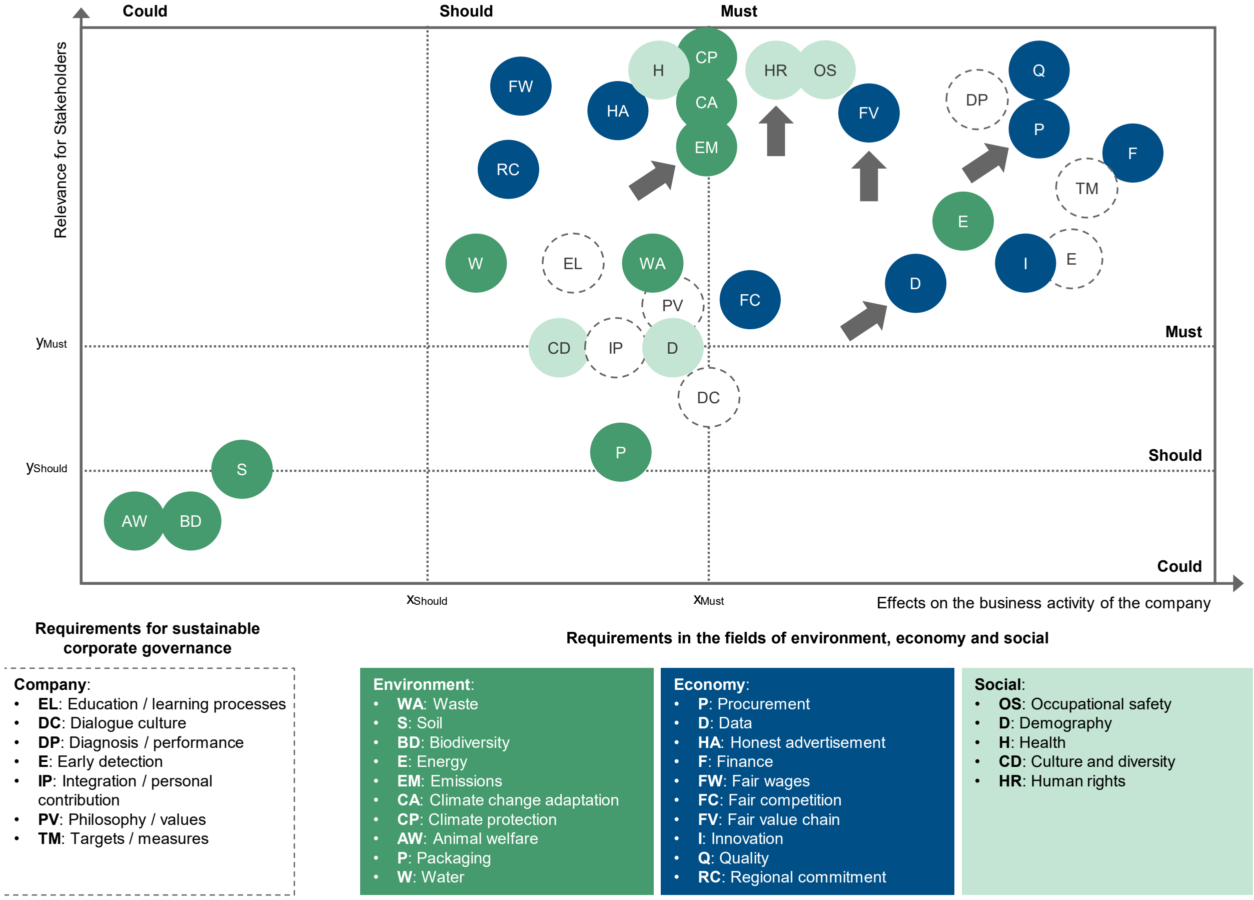

Figure 4: Materiality matrix with exemplary positioning of sustainable fields of actions based on the ZNU standard [43]

In the depicted example, the company has mapped and located the respective requirements across the various categories qualitatively along the matrix. According to the LkSG, the company is obliged, directly and indirectly as a supplier, to observe the human rights and environmental due diligence obligations in its supply chain. In this context, a risk analysis must be carried out in the company's own business area and at direct suppliers. Appropriate preventive measures, including procurement strategies, must be defined to prevent or minimize these risks. Moreover, the company must submit an annual and risk report requiring the relevant data. [5] Additionally customers require proof of the aggregated product carbon footprint (PCF) of the supplied product segments for the continuation of supply contracts. This places a requirement on the emissions for the production and provision of services and the required corresponding data. Thus, emissions, procurement, and data have an increased relevance for stakeholders as well as for the profitability of the company. Human rights and a fair value chain have become a priority for stakeholders, which must be fulfilled by the LkSG that has come into force. In figure 4, these exemplary developments are represented by arrows.

In accordance with the classification in the materiality matrix, these requirements are given a higher weighting in the goal-setting process and thus in the resource allocation decision-making process. In the given example, the understanding of system quality evolves from the design of supply chains that meet the requirements of customers to a supply chain that meets the requirements of a broader stakeholder group. At the same time, additional customer requirements related to fair value chains and regulatory compliance are implicitly considered in terms of the ESG spectrum.

The rebalancing of requirements poses a challenge for companies to adjust their internal mechanisms and processes. For instance, in the case presented earlier, it is crucial to define and monitor new key performance indicators (KPIs), which requires the effective generation and use of data. Such changes in the target system naturally call for the development of company capabilities. These adjustments need to be approached from an operational perspective.

3.3 Operational Perspective

Possible design fields of the operational perspective are the establishment of quality control loops and the provision, steering, and efficient use of the required resources. [10] Increased consideration of ESG criteria thus has significant implications for quality planning, assurance, control, and improvement in the enterprise. Furthermore, this affects the use of technologies and methods as well as the involvement and training of employees in these quality areas. In particular, the focus lies on the interactions between ecological sustainability and the understanding and management of quality in the product life cycle. In terms of ecological effectiveness as a sustainable production strategy, the aim is to achieve closed resource utilization cycles instead of a linear resource utilization. [48] This is achieved with the aid of various so-called "R-strategies", including “Reuse”, “Refurbishment” and “Remanufacturing”. [49] These R-strategies represent a change for the definition of quality requirements for products and production processes, ranging from quality planning to the definition of appropriate quality assurance measures and cooperation with suppliers in the context of quality control [50]. From a process perspective, the avoidance of waste is already anchored as a principle by lean management [36]. Depending on the industrial sector, possible parameters include energy, water, and material consumption as well as waste, production rejects and emission quantities. [42] Ecological efficiency as well as the reporting of these efficiency parameters are playing an increasingly important role as essential prerequisites for the quality of a process.

Figure 5 shows a KPI system developed at the WZL | RWTH Aachen University for input-output-based sustainability assessment of production pro-cesses. Divided into 19 sustainability factors of the dimensions environment, social and economy, the model is based on a total of 107 sustainability indicators (environment: 32; social: 31; economy: 44). In deriving these indicators, 615 parameters were identified in a literature search and condensed by means of a cluster and materiality analysis. The presented model can be used for structured measurement of the sustainability perfor-mance of production systems. This enables the identification of undesirable develop-ments and optimization potentials at an early stage, as well as the definition and initiation of countermeasures. [51]

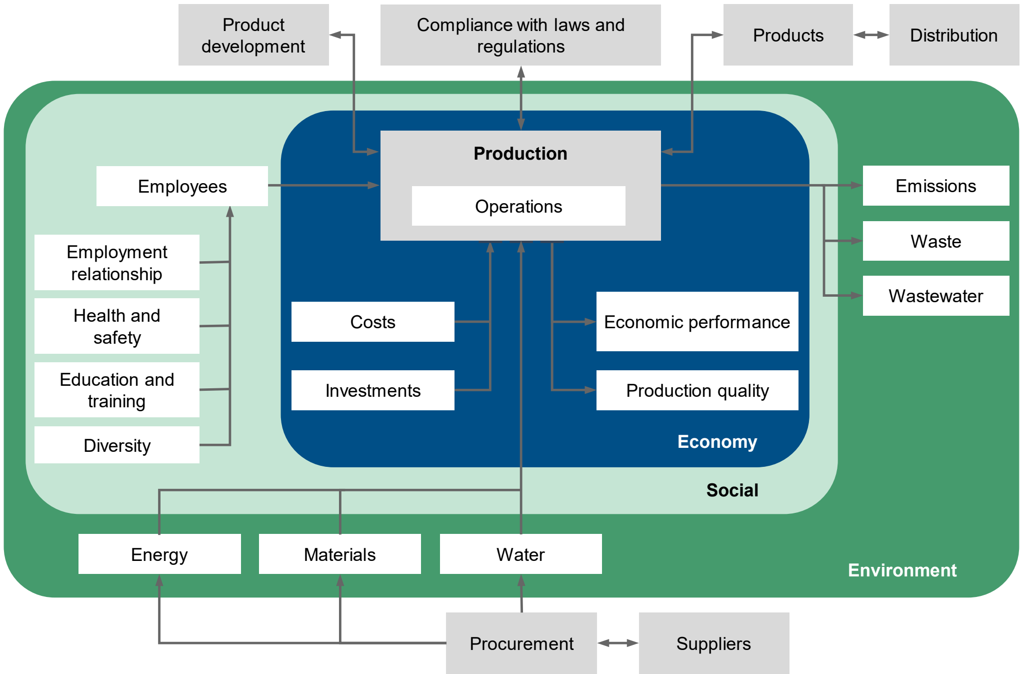

Figure 5: Input - output based KPI model for sustainability assessment. [51]

The derivation of reliable KPIs for controlling and regulating sustainability initiatives re-quires including a wide range of information. This increases the need for suitable struc-tures for generating, managing and utilizing data. Despite several initiated digitization ef-forts, this can still pose a challenge for companies. Data management forms the basis for the efficient use of advanced analysis methods, as it significantly influences subsequent results and interpretations. [52] Accordingly, data is understood as a valuable resource dependent on the existing data quality. Data management harmonized within the compa-ny's data architecture and considering cross-value chain influences is a competitive and quality factor. [53]

The development or improvement of sustainability-oriented data management systems requires the targeted identification and acquisition of new data and the integration of dif-ferent data sources and systems to create an extended knowledge base. Starting from the creation of an understanding of relevant data sources and collection systems, require-ments for data preparation and their provision are defined. In this context, the different dimensions of data quality (e.g., data quantity, structure, and completeness) must be considered. [54] This is supported by the selection and development of a suitable digital infrastructure. The key principles to be considered in this context include freedom from redundancy and low-effort recording (process orientation), mechanisms for system maintenance and clear responsibilities (system orientation), as well as traceability and analysis capability (data orientation). In addition, systems must be designed in such a way that a centralized access point for data retrieval and the integration of third parties is available (for example, through external applications), even in the case of decentralized stored data. [52], [55] The data basis created enables advanced data analysis and the subsequent derivation of data-based decision-making in the sense of continuous improvement. For the implementation of quality improvement measures in the company, existing mechanisms and methods of quality management can be used. In contrast to the already established approach, ESG criteria become optimization targets or constraints and are hence explicitly included in the definition of target achievement and project quality.

While for the presented company example the risk analysis and the reporting of the LkSG can be assigned a responsibility within the company, the calculation of the PCF and the development of the necessary data infrastructure and basis require a project structure. Here, classic approaches and methods of lean management based on the PDCA or DMAIC cycle can be applied in a cross-functional team. A sustainability management function can take over a coordinating role in the project. Once the objectives have been defined, proven methods such as Makigami, value stream mapping or Gemba Walks can be used to identify possible levers and to define requirements and project scope in detail. The requirements for the data, including the necessary infrastructure, interfaces, and integration and analysis concepts, are defined specifically to address ESG criteria. In this context, further quality criteria can be interpreted regarding a specific purpose, such as the trustworthiness and security standards of the data for the calculation of the PCF. Known control concepts, such as audits, will continue to be used to verify the implemented measures. The sustainable anchoring of the measures is achieved through training and showcase examples. In this context, the competencies, and attitudes of employees toward sustainability are of great importance for the success of sustainability projects.

For further consideration of the practical example, the calculation of a PCF along the supply chain is illustrated. Due to inaccurate data, this is often only possible using static assumptions and estimates. However, in order to be able to identify optimization potentials precisely and reliably, upstream and downstream supply chain players must use a common, reliable database as the basis for PCF calculations. Derived from this, there is an increasing need for networking and date exchange within supply chains over time. However, since emission data can also be traced back to sensitive company data such as production processes, their disclosure will not take place without adequate security measures. The transfer of emission data is only secure if companies are guaranteed encryption of communication and sovereignty over their own data. Therefore, a software and communication platform are needed along the supply chain that meets these requirements. Figure 6 schematically shows the communication and material flows of an exemplary supply chain between OEM and Tier-1 and Tier-2 suppliers. Each company communicates directly and encrypted with the software, so that the others can use the calculation results but do not have access to the individual data.

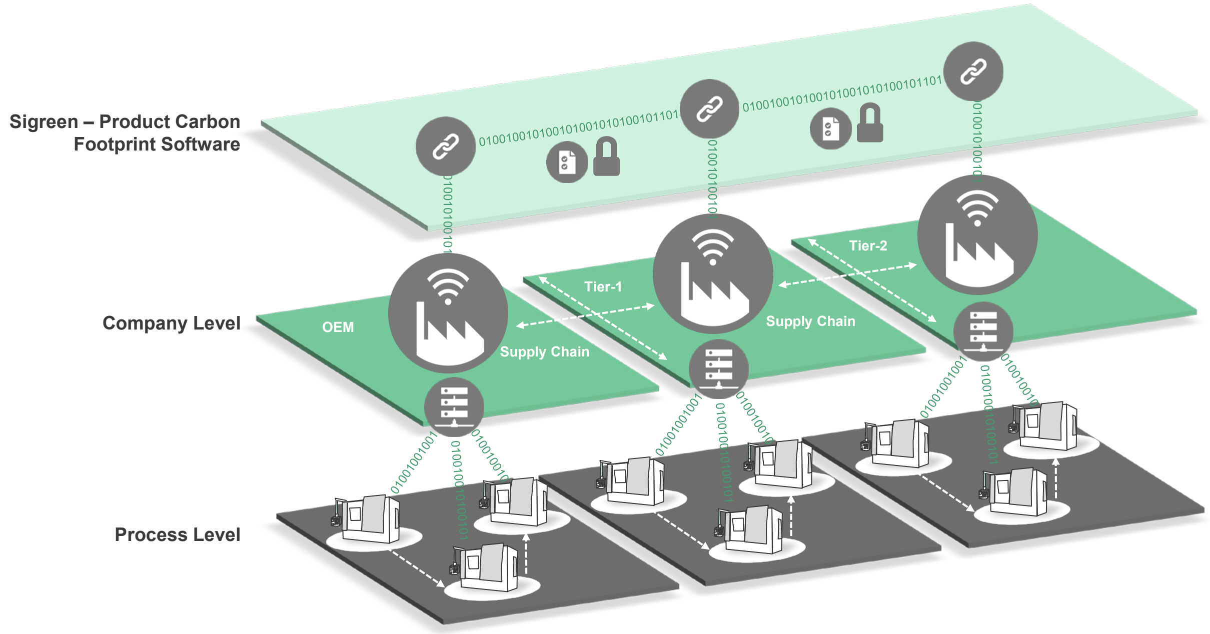

Figure 6: Schematic representation of the communication of emission data for the calculation of the PCF along a supply chain using Sigreen

Siemens AG has already developed a corresponding software solution for the described scheme. Sigreen's underlying technology TSX (Trust-worthy Supply Chain Exchange), creates a reliable database through data encryption to calculate dynamic PCF. [35] Data can be exchanged via interfaces such as API or Connect. Members of the supply chain only see the final calculation and keep control over sensitive production data. This trust enables the precise calculation of emissions and, thus, the joint decarbonization of the supply chain. The software includes different standards to achieve reliable results even with different calculation methods.

To support the decarbonization of supply chains, Siemens AG co-founded the ESTAINIUM network [56]. The network is characterized as an association of universities, certifiers and companies of different sizes. The association aims to promote the members' exchange on industry decarbonization. It also aims to consolidate many existing standards (see Chapter 3.1) and define future-relevant topics in cooperation with sustainability pioneers from various sectors, non-governmental organizations, and certifiers.

4 Implications for Quality-oriented Manufacturing Companies

Many initiatives and demands for circular economy products and services can only be implemented economically and sustainably if the company's structures and processes have a correspondingly effective and efficient design. In the long term, this implies a closed loop between market requirements and the company's product and service provision. In this way, the requirements are met gradually and, in the long term, shape the understanding of quality and the quality expectations from the market perspective, for example, with regard to the responsible use of resources.

However, this development can be carried out not only through a company-side reaction to market requirements, but also through actively shaping the market based on the service offering. Through the targeted introduction of innovative and sustainable services, customers and other stakeholders can be shown new ways, and a broader understanding of quality can be initiated under the aspect of sustainability. However, this applies not only to the product's design but also to the aspects associated with its creation. The company example showed that the transparency of processes along the supply chain and the trustworthiness and security standards of the data represent new forms of process quality. Actively shaping the understanding of sustainability through the anticipation of requirements can serve as a definition of new quality standards that set the definition of quality in the long term. Thus, the development of the paradigm from the market perspective becomes an interplay of *market pull* and *market push* of sustainability initiatives that define the new requirements and standards of the future.

In addition, the operational perspective and the associated fields of quality planning, assurance, control, and improvement play an essential role in the tactical and operational activities of quality management, which are reflected in the long-term system quality of the company. It should be noted that the core activities of quality facets will not change fundamentally. Only the underlying optimization direction, derived from the goals and criteria of the quality policy, is about to undergo a comprehensive transformation. For example, ESG and circular economy criteria are incorporated into the definition of quality requirements and the quality gates of processes. This is particularly relevant for defining quality criteria for production processes that use recycled, remanufactured, or refurbished components. Furthermore, the responsiveness to scarce resources and a product and production strategy transformation to an R-strategy will play an essential role in quality planning. Due to shortened product life cycles, this requires a close coordination with other departments, suppliers and customers, and affects the definition of quality standards and the expectations on the provided products and services.

The economically efficient design of the aforementioned strategies can only be achieved if ESG criteria are anchored in the operational elements coordinated by quality management: Processes, competencies, resources, communication, operational planning and control, requirement engineering, KPIs and data management. The development and implementation of ESG initiatives along quality management functions, from planning to assurance to control, can only be carried out in internal, coordinated interfaces.

Based on the development of norms, standards and certificates, industry-wide data standards are needed to enable interoperability. Therefore, there is a need for an ecosystem for developing new initiatives and quality standards regarding ESG criteria that proactively drive technological development as an enabler of sustainability.

The inclusion of ESG criteria in quality improvement means their explicit consideration within the objective function or the constraints for deriving optimization measures. By enhancing quality management as described above, the quality control loop is closed for the extended requirements of the interest groups. The further development of the various quality management functions is summarized in figure 6. In their entirety, these form the new quality paradigm.

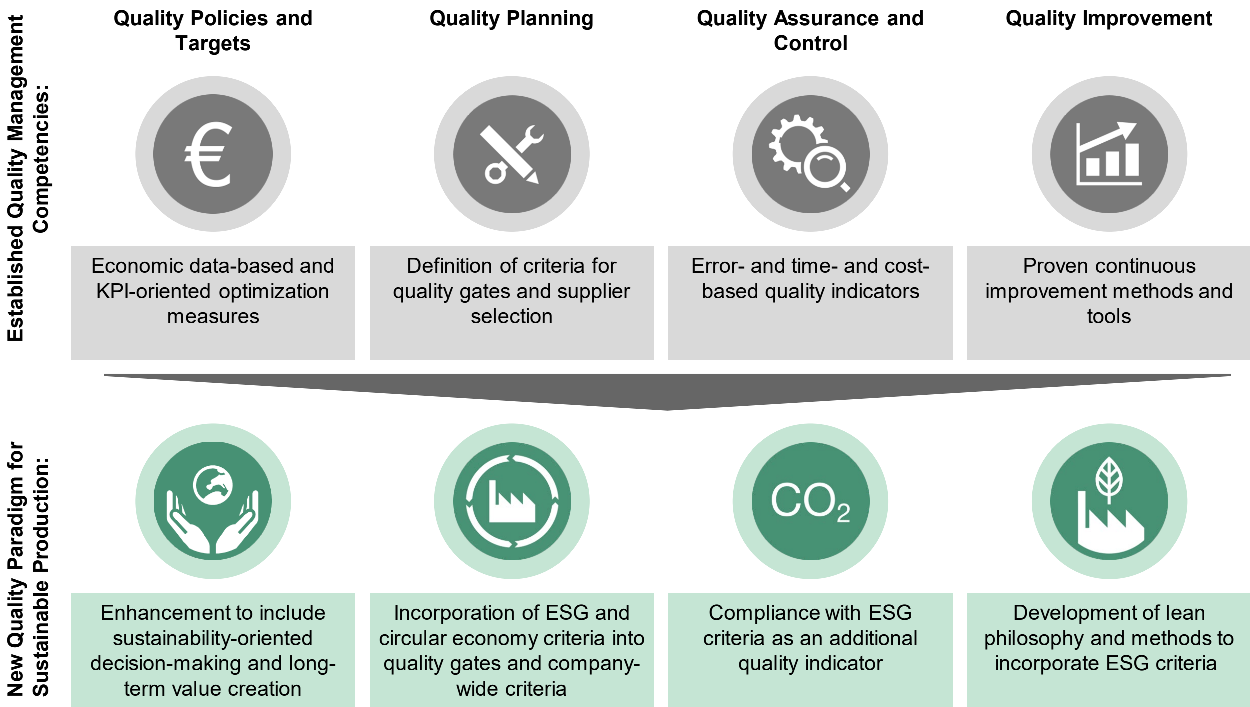

Figure 7: Paradigm shift for quality in sustainable production

From the analysis along the perspectives of the ACQMM, it becomes clear that ESG initiatives must be driven by corporate management and taken into account within the strategy and goal-setting processes. The systematic and process-oriented implementation of these goals from an operational perspective does not require a fundamental redesign of existing mechanisms and methods but rather a redefinition or expansion of the current understanding of quality and quality assessment.

5 Conclusion and Outlook

The historical development of the relationship between the economy, production, and quality management, as well as sustainability trends, indicate a paradigm shift. ACQMM provides a framework for designing quality-oriented activities and analysing levers for internal company changes. It is based on three possible perspectives for the design of company activities: market, management, and operational. The market perspective considers the various interest groups that a company must address, and their changing requirements for quality. The materiality matrix is a useful tool for analysing requirements, showing both their relevance to stakeholders and their impact on company profitability. Based on the *Kano* model, the analysis tool divides sustainability requirements into *must*, *should*, and *could* categories, with a hypothetic temporal development from *could* to *must* requirements in the long term, which is reflected by the institutionalization of initiatives in guidelines, standards, and laws.

The evaluation of the requirements from the market perspective is translated into goals and decisions by the company management. The operational implementation of the set quality objectives influences the design of process quality in the company. This concerns particularly the definition and the understanding of quality criteria in the function's quality planning, quality assurance, quality control and quality improvement. The classic methods and tools from quality management for optimization purposes can be adapted and expanded according to the principle of lean management with an increased ESG focus. Here, interactions arise between the requirements of the product development process regarding environmental sustainability and the design of quality requirements and activities. R-strategies such as "Reuse", "Refurbishment" and "Remanufacturing" can be mentioned here as an example. For the targeted application of the measures outlined, suitable structures for the generation, management and use of relevant data are required. To master this expansion of the control loops in the operational perspective, a future-proof data management system must be able to integrate existing data structures and build new ones. The importance of data was demonstrated using the example of the exchange and reporting of PCF data based on the Sigreen solution from Siemens AG. In this context, the purposeful design of data systems as well as data fidelity are evaluated as further ESG-related quality criteria in the system and process quality of a company. It is assumed that these quality dimensions are prerequisites and success factors for the successful implementation of cross-company sustainability initiatives.

On the one hand, analyses that are already embedded in sustainability-oriented standards and legal requirements can support an effective and efficient interpretation of stakeholder requirements and a consistent implementation in goals and decisions. Both the design of sustainability-oriented management systems and the operational implementation of initiatives are supported by existing systems, methods and tools of quality management. Here, a sustainability-oriented definition of the requirements for systems, quality functions and methods is necessary. After all, in an increasingly productivity-oriented economy, data form the basis and key factor for enabling internal and external corporate sustainability initiatives. However, this does not only include information about a product and the processes that go into its manufacture, as in traditional quality management. Rather, in the future, information about where a product is and in what condition it is in due to its conditions in the use cycle will become decisive in order to achieve a life cycle extension through value enhancement or to make a higher variance of the materials used in the (renewed) production cycle controllable.

The integration of the paradigm of sustainability into the understanding of quality thus offers the possibility for further approaches to investigation. For a comprehensive understanding of the market perspective, the interactions between stakeholders with respect to sustainability should be investigated in more detail. Thus, a tool set for sustainability optimization can be developed. Furthermore, it is necessary to check which of the methods and models can be identified as suitable for different use cases. The exact requirements for the described integrated data management system also need to be considered in more detail. The potential seen in the consistent digitization of processes for the efficiency of production could also be used to increase sustainability through the analysis of consistent data. From the point of view of quality management, the gain in knowledge, the clarification of production-technical or application-side aspects, takes on greater significance. The transparency and enlightening nature of the new quality paradigm regarding the need to consider sustainability motivates a new definition of quality management. The collection, evaluation and consolidation of data into knowledge and the linking with sustainability-oriented impact models to options for action promote the change from *Quality Management* to “*Quality Intelligence”*.

Sustainability-oriented transformations present companies with the challenge of reconciling profit generation and sustainability requirements. The implementation of sustainability aspects to meet the legal requirements is associated with a high technical and organizational effort. Regarding the long-term establishment of this legal requirement, quality management will play an important role for efficient implementation. A rethinking of sustainability and quality will be required both at the level of employees as enablers in production activities and at the level of consumers as buyers. The transformation of quality management could represent an innovative concept to enable sustainability initiatives within the company for cost-efficient production. This applies particularly to the R-strategies and sustainability-oriented data management systems for production. Here, applied research in cooperation with companies can be used to test new concepts. Promoting ecosystems to test and validate these concepts is a necessary step. An example of this is the ESTAINIUM association. This can contribute not only to the further development of technical solutions, but also to the further development of standards and interfaces that enable interoperability across companies. Regarding the reorientation of the understanding of quality, this can also represent an opportunity to measure the degree to which this paradigm shift can be useful in developing and introducing new sustainability-oriented business models for manufacturing companies.

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The content of presentation 4.3 was elaborated by the authors together with other experts in this working group:

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Panel Discussion 01

Data value to empower sustainability

Data value to

The panel discussion highlights the importance of data and its value for sustainable manufacturing. The discussion will focus on the interconnection and collaboaration of companies along the entire life cycle.

Green production promotes the resilience of our value chains and calls for a cross-company and cross-domain approach. This requires the fresh ideas of non-profit research institutions to invent new methods and technologies and develop them in a way that enables the balancing act between protecting corpo-rate interests and leveraging data across company boundaries.

Prof. Dr.-Ing. Robert H. Schmitt

Director of the Chair of Production Metrology and Quality Management, WZL | RWTH Aachen University and Director, Fraunhofer IPT

Host

Achieving Net Zero by 2040 is a key pillar of the Ericsson strategy. With our customers we break the energy curve when moving to the 5th generation of cellular technology and implementing use cases that contribute to sustainability.

Joe Willke

Head of Center of Excellence 5G Industry 4.0, Ericsson GmbH

Co-Host

empower sustainability

We can only operate successfully if we extend existing system boundaries and establish cross-company collaboration models while safeguarding in-house expertise.

Dr.-Ing. Jan Kantelberg

R&D Manager Lead Architecture,
Vaillant Group

For the upcoming industrial transformation, e.g., the establishment of a European production of energy storage devices such as lithium-ion batteries, it is necessary to include the innovation potential of the entire supply chain, especially small and medium-sized enterprises. Digital methods can help to develop new, energy- and resource-saving solutions across companies.

Dr.-Ing. Stephan Witt

COO,
Jagenberg Group

We need more data rivers, and not data lakes.

Dr. Arno Zinke

Senior Vice President Software Engineering,
Hexagon AB

Co-Host

Panel Discussion 02

User stories in circular production

The panel discussion will debate the contribution that user stories as digital product files can offer towards profitable circular production. The discussion centers on the question of whether systemically conceived user stories can be implemented by SMEs at all – or whether this will remain an exclusive tool for global players.

We have to stop taking too narrow a view of sustainability – we will only realize the real "double-digit loot" when we manage to achieve an alignment of ecological and economic objectives in the value creation system by means of circular production!

Prof. Dr.-Ing. Dipl. Wirt.-Ing. Günther Schuh

Director of the Chair of Production Engineering,
WZL | RWTH Aachen University and Director, Fraunhofer IPT

Host

Digitization is the most important lever for successfully implementing circularity – from design and production to sustainable operation and recycling.

Dr. Annika Hauptvogel

Head of Technology and Innovation Management,
Siemens AG

Co-Host

User stories

in circular production

We already have all the tools for greener production today. To make our contribution, we need to think and act in a consistently sustainable way. It comes down to all of us.

Dr.-Ing. Philipp Jatzkowski

Head of Quality and Metrology Consulting,
Testo Industrial Services GmbH

We need transparency and knowledge transfer in the supply chain to jointly develop trust across company boundaries. The result is sustainability in the most efficient use of resources, which is also economically successful. For this, the interaction of technical expertise and academia is essential.

Jens Gerhard

Head of Technology & Process Development,
Feintool System Parts Jena GmbH

Circular production will require even greater digital networking across corporate boundaries. In Europe, we therefore urgently need to work on our digital sovereignty to reduce dependency in the area of critical digital infrastructure. Otherwise, we face the risk that production facilities designed "as a service" will soon be able to be shut down at the push of a button.

Dr.-Ing. Tilman Buchner

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About this book

"Empower Green Production" is the guiding theme of the 31st AWK, which will point the way to a value-adding circular economy in four parallel lecture series with a total of twelve technical and keynote lectures as well as eight plenary lectures from science and practice from May 11 to 12, 2023.

This conference proceedings uses numerous concrete examples from current industrial and research projects to describe which technologies and strategies will promote this transformation, how companies can select their individual tools for the change from the wealth of methods available, and which challenges applied production research can specifically support. The four central thematic blocks of the AWK include contributions on high-performance and resilient data infrastructures, on modelling and analyses with the aim of more resource-efficient manufacturing, on scenarios and business models for sustainable value creation, and on technologies and processes for a value-adding circular economy.

This book summarizes the contents of the lectures, makes it avaccessible and intends to inspire the scientific community and the interested specialist audience in the form of an open access publication. Its individual contributions were compiled and elaborated by the staff of the Laboratory for Machine Tools and Production Engineering, WZL | RWTH Aachen University and the Fraunhofer IPT, Institute for Production Technology together with re-nowned experts and speakers from industry, economy, science and politics.

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