How can industrial management contribute to a brighter future?

Jochen Deuse (Ed.)

WGAB

Schriftenreihe der Wissenschaftlichen Gesellschaft
für Arbeits- und Betriebsorganisation (WGAB) e.V.

GITO

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ISBN 978-3-95545-412-8 (E-Book) | DOI: https://doi.org/10.30844/wgab_2023

Bibliographic information of the German National Library

The German National Library registers this publication in the German Nationalbibliography; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

Published at GITO Verlag 2023
Printed and bounded in Germany, Berlin 2023

GITO mbH Verlag
für Industrielle Informationstechnik und Organisation
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Introduction

Industrial management has many opportunities to contribute to the future with one of the most important being promoting sustainability. By adopting sustainable practices, industrial management can help reduce waste and pollution, conserve natural resources and protect the environment. Industrial management can help workers acquire new skills and knowledge by providing employees with training and development opportunities that will enable them to succeed in the future. This not only benefits workers but also helps companies attract and retain top talent, which in turn can assist to better address current and future challenges.

This year, the WGAB follows the motto "How can industrial management contribute to a brighter future?" in order to address the global requirements for climate protection and the associated three pillars of sustainability – economy, ecology and social issues – through technical approaches.

Thanks to the creativity and proficiency of this year's authors, this book contains a wide range of research approaches and methods that contribute in line with this motto. It covers research fields of maintenance-free and resilient production, material flow planning as a model for public transport, circular economy networks, employee management and planning. Additionally, new approaches and integrated digital twins for mapping product life phases are also presented.

I would like to thank everyone involved in helping to produce this book.

Sydney, September 2023
Jochen Deuse

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Maintenance-Free Factory

The Transformation of Maintenance

Wilfried Sihn, Luisa Reichsthaler, Daniel Toth, Linus Kohl, Lisa Greimel

1. Introduction

The inspirations for conducting research activities on the Maintenance-Free Factory (M2F) were derived from the contemporary challenges and goals to achieve more sustainable and efficient ways of working in industrial maintenance and production. The increasing complexity and criticality of industrial machinery has made maintenance a fundamental aspect of production management. Unexpected breakdowns can lead to significant risks and consequences, requiring a focus on machine reliability, availability, maintainability, and safety. In particular, asset-intensive industries such as manufacturing companies focus on controlling maintenance costs while achieving these goals (Bousdekis et al. 2015; Golpîra/Tirkolaee, 2019).

Fortunately, with the advent of digital technologies such as the internet of things, artificial intelligence, and predictive maintenance, tools are available to improve the identification and preservation of critical resources. Applying these methods results in efficient maintenance and the ability to identify potential machine failures before they occur. Positive outcomes are reduced downtime, increased production efficiency, and minimized risk and consequences of unexpected failur (Jasiulewicz-Kaczmarek/Gola 2019).

The holistic M2F approach incorporates digital technologies and other existing approaches to create a "future maintenance". To achieve a maintenance-free factory, a theoretical concept has been developed:

- **Digital maintenance processes** – involve using digital technologies to increase the efficiency of maintenance activities and improve machine reliability and availability while reducing costs. This paradigm includes all related approaches, e.g. assistant systems.

- **Data-driven maintenance** – includes all data-based maintenance strategies that lead to predictive maintenance, using digital technologies such as sensors, data analytics, and automation to monitor and optimize machine health and Industry 4.0 approaches, e.g. artificial intelligence.

DOI: https://doi.org/10.30844/wgab_2023_1

- **Decision support system** – describes the bi-directional integration of maintenance planning with production planning, business cases, and models. Future maintenance enables higher productivity and fewer breakdowns through informed decision-making.

- **Maintenance staff** – describes various aspects such as ergonomics, skills management, continuing education and training methods, knowledge management, acceptance of new technologies by maintenance personnel, and work organization and flexibility in general.

- **Sustainable maintenance** – includes relevant aspects of sustainability and resilience in terms of energy and resource-efficient system design as well as aspects of circular economy, optimized life cycle of machinery and equipment and life cycle assessment.

2. The necessity of a fundamental change in maintenance

For decades, various approaches have been designed and implemented to optimize maintenance management systems in manufacturing. Increasing digitalization has led to novel data-based maintenance methods and strategies in recent years. Despite plausible benefits for manufacturing companies, maintenance is not yet considered as an enabler and driver of sustainable and resilient production management (Glawar et al. 2022; Sihn et al. 2021).

Advancing digitalization, sustainable legislation at national and international level, and changing employee needs represent current challenges in the industrial context. These challenges have a number of objectives, such as improving the use of resources, practicing efficient energy consumption, minimizing capital expenditure by extending the life of machinery, equipment and spare parts, and changing the expectations placed on production and maintenance personnel. In fact, there is a wide discrepancy in the maturity of the theoretical approaches to maintenance management found in the literature (Simard et al. 2019). Manufacturing processes in most companies have now been optimized to such an extent that only a few productivity gains can be achieved there, but there is still a lot of potential for improvement in the maintenance environment.

Therefore, future maintenance needs a new character under the guiding principle of *"Create value instead of costs!"*.

3. Challenges facing the maintenance sector

Initiating the transformation of maintenance from a cost factor to a value-added partner presents companies with the following prevailing challenges:

- **Doubts about the economic efficiency of maintenance**: Maintenance is often perceived as a non-value-adding activity from a current economic perspective (Henke et al. 2019). In this context, reference is made to the lead time of maintenance orders, 75% and 80% of which are reported non-value-added activities (Matyas 2018). This is a result of paper-based processes, a high proportion of failure-oriented maintenance and the associated mostly unplanned interruptions.

- **Lack of data**: Data availability and quality are the key success factors for data analysis projects (Badraddin et al. 2022). Data availability and quality are fundamental for the implementation of predictive maintenance methods or strategies (Nemeth et al. 2019) and are mostly insufficient (Simard et al. 2019). Different failure scenarios need to be identified to enable accurate predictions and relevant patterns that indicate failure need to be derived. In addition, the common strategy of short maintenance cycles of high-cost and critical equipment results in fewer breakdowns but makes it difficult to infer patterns (Singla et al. 2021). Another reason for poor data quality is the organization's incomplete documentation of maintenance activities and poor knowledge management. Systematic maintenance feedback collections a key success factor for implementing data-based maintenance strategies (Schildkamp/Poortman 2015).

- **Lack of flexibility in the maintenance organization**: Although data-driven and AI-based maintenance approaches can provide a better understanding of when a failure might occur, the inflexible work environment makes it impossible to perform the necessary maintenance activities outside of the production process (Fusko et al. 2018). There often are conflicts between production planning and maintenance about whether and when a time slot can be used to perform the necessary maintenance (Cao et al. 2021). After flexibility, business agility is another important part because being able to work with new conditions and implement them as a standard is a major problem for many companies. Therefore, it is necessary to promote maintenance agility and to implement the new working practices efficiently and in the long term (Eckstein 2015).

- **Shortage of skilled workers in industrial maintenance**: Increasing the attractiveness of maintenance is a key lever for addressing demographic change and retaining skilled workers. The lack of appropriate skills for the transition to digital work systems is also an area for action (Kohl et al. 2021).

DOI: https://doi.org/10.30844/wgab_2023_1

- **Lack of prioritization of sustainability and resilience in maintenance**: Maintenance is still seen as a cost generator, not an economically, ecologically and socially sustainable value driver. There is great potential in the areas of resource use and consumption, energy efficiency and environmentally friendly technologies and materials (Jasiulewicz-Kaczmarek et al. 2020).

To address these challenges, various approaches such as total productivity management (TPM), reliability-centered maintenance (RCM) or lean maintenance have been persuaded to optimize maintenance management (Biedermann/Kinz 2019). However, there has not been a shift in industrial environments from maintenance as a cost driver to a strategic competitive factor (Sihn et al. 2021).

4. The vision of the Maintenance-Free Factory

The Maintenance-Free-Factory (M2F) vision is to harness the potential of digitalization as a driver of sustainability and enable a fundamental transformation of maintenance to solve environmental, economic and social challenges while securing the future and competitiveness of companies. The concept explores the hidden potential to transform maintenance into an enabler rather than a cost driver along the production line. M2F involves designing production processes to be highly resilient to external and internal disturbances, enabling sustainable planning and operation of flexible production processes.

The challenges listed above require a new understanding of maintenance, similar to what has already been achieved in quality management with the "Zero-Defect-Manufacturing" approach and in setup processes with the "Single Minute Exchange of Die" (SMED) approach. In the future, maintenance will be understood to achieve an overall optimum production time. Special attention will be paid to minimizing non-value-added time.

In analogy to SMED, in which the unproductive setup operations are parallelized and thus extracted from the production process, the concept of the M2F pursues the approach of separating maintenance activities from the production process and extracting them from the productive production time (Sihn et al. 2021).

A M2F is defined as the fundamental maintenance transformation to maximize value-added production time. It therefore implies a factory where production processes are free from maintenance activities.

To realize the vision of M2F a concept has been developed, see Figure 1.

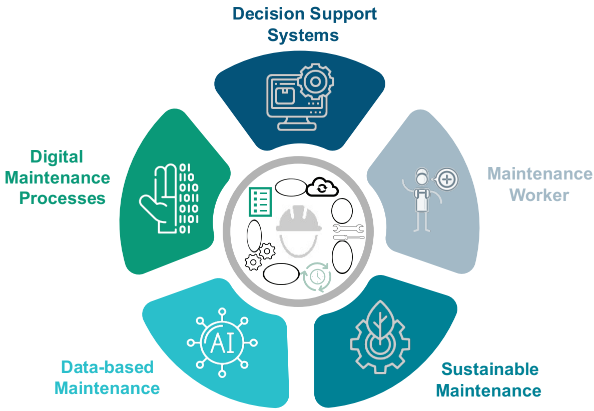

Figure 1: Concept of the Maintenance-Free Factory

The concept includes 5 elements, digital maintenance processes, data-based maintenance, decision support systems, maintenance workers, and sustainable maintenance, which are explained in more detail in the following chapters.

4.1. Digital maintenance processes

Digital maintenance processes refer to the use of digital technologies and software applications to plan, execute and manage maintenance activities in industrial and commercial environments. These processes use various tools and techniques, such as predictive analytics, artificial intelligence, and the Internet of Things (IoT) to monitor equipment performance, detect potential problems, and schedule maintenance activities in a timely and efficient manner.

Digital maintenance processes are becoming increasingly important for several reasons. Firstly, they can help to reduce downtime and prevent expensive equipment failures by identifying potential issues before they cause significant problems. Secondly, they can improve maintenance efficiency and reduce costs by optimizing maintenance schedules, reducing unnecessary inspections, and streamlining maintenance workflows. Thirdly, they can enhance safety by ensuring that equipment is properly maintained and inspected regularly (Crespo Márquez 2023).

Moreover, digital maintenance processes can provide real-time data and insights that can be used to inform decision-making and improve overall business performance. Companies can identify patterns and trends by analyzing maintenance data, optimize maintenance strategies, and make informed decisions about equipment replacement, upgrades, or repairs.

Overall, digital maintenance processes are critical for modern industrial and commercial operations to improve reliability, reduce costs, enhance safety, and stay competitive in today's rapidly evolving business environment (Karki et al. 2022).

4.2. Data-based maintenance

Data-driven approaches seek to improve maintenance strategies by incorporating predictive or prescriptive capabilities (Matyas et al. 2017).

Data-driven maintenance is a proactive approach that uses digital technologies to optimize maintenance activities. It involves using real-time machine data and installing sensors on machines to collect real-time data on its performance, which is then analyzed to predict remaining useful life (RUL) and anticipate any potential breakdowns before they occur. Retrofitting older machines with sensors allows data to be collected from machines that were not originally designed for digital monitoring, contributing to sustainability goals. By analyzing the collected data using machine learning algorithms, models can be developed that predict maintenance needs over time with increased accuracy. This approach can turn unplanned maintenance into planned maintenance, resulting in less downtime and higher machine availability. In addition, downtime can be used for maintenance activities to avoid disruptions to the production schedule (Ansari/Kohl 2022; Jasiulewicz-Kaczmarek et al. 2020).

In summary, the integration of data-driven maintenance and the use of AI methods increases availability, improves product quality, and stabilizes production processes, contributing significantly to the realization of the M2F vision.

4.3. Decision Support Systems

Decision Support Systems (DSS) are computer-based tools that help people make decisions by providing access to relevant data and analytical models. The value of a DSS lies in regular backups, documentation, monitoring, testing, updating, and establishing a maintenance schedule. These practices help ensure that the DSS remains functional, reliable, and effective in supporting decision-making. Regular backups and documentation prevent data loss and facilitate problem resolution, while monitoring and testing identify potential issues and bugs that need to be addressed. Updating the DSS software and systems and establishing a maintenance schedule helps ensure that the system remains secure, reliable, and compatible with the latest technologies (Rodríguez-Padial et al. 2015).

Therefore, a radically different understanding of work organization, the production and maintenance environment is required. Such an organization provides the flexibility to remove non-value-added activities from production. For example, downtime caused by material shortages or production interruptions can be used for maintenance activities.

This requires the integration of maintenance planning into the company's production planning and control and an optimized communication between the parties involved. Production gaps, and thus possible maintenance times, are identified in time and filled according to an ideal maintenance strategy. All other maintenance activities take place outside of production time, see Figure 2.

Focusing on planning and predicting maintenance activities to reduce unproductive, unplanned interruptions using appropriate, data-driven methods. The goal is to proactively manage and schedule processes and make decisions about actions to be taken, despite increasing complexity.

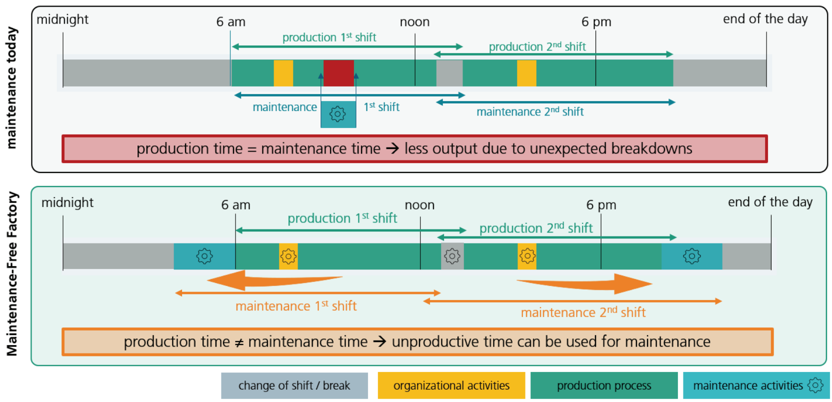

Figure 2: The Maintenance-Free Factory – when should maintenance be done? (based on Sihn/Greimel, 2023)

This is accompanied by a change in job descriptions in the industrial maintenance field towards "resilience expert or manager" with a focus on data science competencies. The reduction of short-term operational activities implies an increase in analytical activities and strategic elements. The latter range from knowledge management challenges, changing employee competence profiles and qualifications, to a holistic new work aspect (Glawar et al. 2022; Sihn/Greimel 2023).

4.4. Maintenance Worker

Due to the significant increase in digitalization and automation, as well as the complexity of production equipment, the competence requirements for maintenance personnel have changed, both on the front end (i.e. blue-collar workers on the shopfloor) and on the back end (i.e. white-collar workers responsible for planning,

DOI: https://doi.org/10.30844/wgab_2023_1

monitoring, controlling and managing). Maintenance managers in the era of Industry 4.0 face major challenges in reducing unwanted outputs (e.g. CO_2 emissions), reducing equipment downtime, lowering costs, meeting desired production lead times and doing all this with less risk to safety and cybersecurity while avoiding damage to the environment. The competence profile of workers is also being transformed by integrating intelligent assistance systems such as conversational AI and physical assistance systems into maintenance work systems. On the one hand, they benefit from technologies that improve work efficiency and quality, for example in documentation (Ansari et al. 2021). On the other hand, they need to become more flexible in terms of knowledge sharing and work-integrated learning (Nixdorf et al. 2021). Considering Industry 4.0 technologies, in particular information and communications technology (ICT) and operational technologies (OT), the ability to collect, analyse and visualize data increases significantly. As a result, maintenance blue- and white-collar workers and consequently business managers can benefit from the value of data in troubleshooting, planning, monitoring and controlling activities. Effective data analysis in the circular value chain enables OEMs and machine users to deepen their understanding of equipment, processes, services, employees, suppliers and regulatory requirements (Jasiulewicz-Kaczmarek et al. 2020).

In the future, people will still be essential to maintain, monitor and ensure the safety of equipment and production machines. In this sense, maintenance and repair tasks will not become redundant in M2F, but their nature will change. New competencies and skills will be required, while some of today's competencies and skills will become obsolete. However, maintenance tasks will increasingly tend towards cognitive tasks and will be strongly characterized by knowledge transfer from experienced workers in production systems (Ansari 2019). Accordingly, the understanding of the role of maintenance will also change, i.e., the entire value chain and the circular ecosystem of maintenance will have to be taken into account.

4.5. Sustainable Maintenance

In the future, maintenance will be more than just a set of activities to deal with breakdowns and failures and preserve machinery and equipment. It is more like long-term strategic planning that integrates all phases of a product's life cycle, incorporates and anticipates social, environmental and economic changes, and takes advantage of innovative technologies. The emphasis on adopting environmentally friendly practices, implementing sustainability measures and protecting the environment has continued to grow. National and international legislation, the increasing importance of sustainability, and environmental protection are putting more pressure on industrial companies to focus on sustainable manufacturing practices (Ghafoorpoor Yazdi et al. 2019). Maintenance in a manufacturing company, as a function of great importance, must also contribute to sustainable practices. However, the maintenance process significantly impacts not only the volume, cost of production, and quality of the final product, but alsohe safety of people and the natural environment (El kihel et al. 2022). As a result, in companies that benefit from the so-called good engineering practices, maintenance is not only a cost to be avoided, but mostly an active operation that can become an effective input to the company's development and an integral part of its sustainable development strategy. Therefore, it is necessary to include the category of sustainable development in the processes and activities realized in the area of maintenance of the enterprise's technical infrastructur(Jasiulewicz-Kaczmarek 2013). It requires developing a maintenance strategy and a set of goals consistent with the corporate strategy and the commitment and participation of all employees, as well as knowledge, experience and consistent performance (evolutionary nature of the process). For example, this can save valuable resources by extending machine life and/or reducing energy consumption by increasing machine reliability.

5. Summary and outlook

In contrast to existing approaches in the field of maintenance, the revolutionary and challenging M2F approach aims for a holistic view of value creation processes, including the needs of employees, sustainability and resilience requirements, as well as the technical possibilities offered by digitalization.

Thus, the key next steps in implementing the maintenance revolution and research priorities are:

- Data utilization: Consistent implementation of data-based maintenance (predictive / perspective maintenance) to reduce the proportion of malfunctions and convert malfunctions into plannable maintenance activities
- Planning: Integration of maintenance planning into production planning in order to use downtimes consistently and in a plannable manner
- Flexibility: Design a new, flexible working time model in maintenance so that maintenance can occur when production is not taking place.
- Sustainability: Incorporating the sustainability aspect into maintenance in order to carry out activities as resource-efficiently and efficiently as possible and to solve social challenges
- Roadmap: Development of a step-by-step approach for the implementation of M2F in industrial practice.

With the Maintenance-Free Factory, maintenance is to become a driving force for sustainable production management, coordinated and planned within the framework of production activities and thus an integral part of the overall corporate strategy, paving the gap for the paradigm shift towards maintenance as a competitive factor.

DOI: https://doi.org/10.30844/wgab_2023_1

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Conceptual Design of a Decision Support System for Material Flow Planning and its Transfer to Public Transport

Christoph Ecker, Matthias Hayek, Martin Riester, Wilfried Sihn

1. Motivation

The trends of increasing value creation, customer orientation, sustainability, and digitalization are putting manufacturing companies under increasing pressure. Existing, established production and logistics systems can no longer fully meet these additional requirements regarding flexibility and dynamics. Inefficient and non-transparent material flows arise. Currently and in the future, most material transports are done manually (e. g. using forklifts). Challenges such as long throughput times, poor utilization of transport systems, and long transport distances result. To achieve economic, technical, organizational, and sustainability objectives, manufacturing companies are faced to optimize these weaknesses. Therefore, material flow planning is performed (Pfohl 2023; Chakraborty/Saha 2022; Berndt et al. 2021; Dickmann 2015). Concept planning is the first planning phase. It includes the identification of potentials, the development of different technical concepts, and the preparation of decisions for the selection of the preferred one (Martin 2016; VDI 2498 Part 1 2011). However, problems arise when performing material flow planning due to poor data quality, missing data, and complex decision-making. In many cases, these lead to one-dimensional, isolated, and suboptimal planning results and high efforts for planning (Burggräf et al. 2021; Dickmann 2015).

The reasons are outdated and qualitatively insufficient data without reference to actual processes (Hosseini-Nasab et al. 2018), errors in the double-digit percentage range in data from IT systems (Dickmann 2015), high efforts for data procurement (e. g. interviews, observations) (VDI 2689 2019), untapped potential of digitization solutions such as sensors (Hayward et al. 2022), and a lack of decision support in planning (Burggräf et al. 2021).

Therefore, this paper aims to develop a concept for a decision support system for optimizing forklift material flows based on sensor data. On the one hand, the efficiency and the data-drivenness of material flow planning shall be increased. On the other hand, this decision support system provides the mathematically optimal result regarding the layout arrangement of sources and sinks, the forklift deployment and the order allocation, and the selection of optimal forklift types including

DOI: https://doi.org/10.30844/wgab_2023_2

proven automation. This should contribute to reducing logistics and material flow costs in manufacturing companies. In addition, the transferability of this concept to public transport is to be evaluated. This should determine to what extent industrial management methods can be used outside of factories and how these methods contribute to creating a sustainable future.

To achieve these aims, the following structure is chosen for this contribution. Section 2 discusses related work of sensor-based decision support in logistics and decision support systems for material flow planning. Based on these related works, a sensor-based concept of a decision support system for optimizing internal forklift material flows in manufacturing companies is developed and discussed in section 3. Since the logistics challenges on the last mile are like those of internal material flow, section 4 provides an outlook on the transferability of this in-plant concept to crowdsourcing delivery using public transport. This is done during the Öffi-Packerl research project. Finally, the results are summarized and an outlook on further research is given.

2. Related Works

As discussed in section 1, the complexity and dynamics of logistics and material flow are continuously increasing. Making correct and forward-looking decisions in planning processes to minimize consequential costs and additional efforts is becoming increasingly important (Ben Rabia/Bellabdaoui 2022). Amulu Priya et al. (2021) state that using operations research methods is necessary to achieve data-driven, efficient, and analytical optimization of logistics processes. For this purpose, the logistic decision problems are modeled mathematically and solved using exact calculation methods, heuristics, multi-criteria decision-making (MCDM), and simulations (Yazıcı et al. 2022).

- Linear programming is an exact method to calculate an optimum under constraints. Types of linear programming are integer, dynamic, and goal-oriented linear programming.

- Heuristics are used when problems cannot be represented using exact calculation methods or the calculation is too time-consuming. These methods provide results close to the optimum and can be implemented globally as a meta-heuristic or locally as problem-specified optimization.

- MCDM supports the solution of multiple decision problems when different solution variants and alternatives exist and an optimally suitable one is to be selected. MCDM are classified into benefit-based and superiority-based methods with various characteristics.

- Simulations model the properties of systems using parameter variations and support decision-making, as impacts on the existing system can be evaluated before a new, adapted, or revised system is introduced (Yazıcı et al. 2022).

2.1. Sensor-Based Decision Support System

Decision support systems (DSS) are computerized information systems to support management decision-making (Yazdani et al. 2017). Such Systems consist according to Ben Rabia and Bellabdaoui of three interacting layers (2022): data, model, and knowledge layer.

- The data layer collects, manages, and prepares the database for solution finding, which includes structured (e. g. ERP data), semi-structured (e. g. sensor data), and unstructured data (e. g. text or image files).
- The model layer solves complex problems and provides a toolbox of operations research and simulation methods.
- The knowledge layer prepares the knowledge generated by the system for decision-makers using mathematical models and data analysis.

A DSS requires knowledge of the current and future status of the decision-making system. This includes orders, resources, entities, and processes. An inadequate database and a low real-time reference make decision-making difficult (Korth et al. 2018; Marinkovic et al. 2023). Therefore, the importance of real-time information is increasing. Sensors and Internet-of-Things applications are used for this purpose (Ben Rabia/Bellabdaoui 2022; Coelho et al. 2021). First, sensor-based decision support systems have already been discussed in related works. Estanjini et al. (2011) use a sensor network to optimize forklift dispatching. The data regarding duration of use, collisions, battery level, and position of the forklifts are collected based on sensors. The generated and processed data is then used in a decision support system that uses heuristics to optimize the forklift dispatching. Müller et al. (2018) develop a decision support system for an industrial laundry to schedule picking and transport orders optimally in real time. RFID (Radio Frequency Identification) tags are attached to the laundry to track its location. Booking data is used to identify the vehicle's position. In the simulation-based methodology of Kibira et al. (2015) to support the planning of manufacturing processes, data input is based on sensors. Ecker et al. (2023) show that sensor-based material flow planning can optimize sustainability criteria of manufacturing companies such as energy efficiency besides economic ones.

2.2. Decision Support for Material Flow Planning

The following section summarizes related works that provide decision support in material flow planning. The authors consider the areas of order allocation of transports, selection of transport systems, automation of transport systems, and layout planning. Sensors are not used for data collection in these works. In Coelho et al. (2021) and Carli et al. (2020), additional real-time information through sensors is specified as a need for further research.

Carli et al. (2020) develop a decision and control model to assign transport tasks optimally to electric forklifts. The aim is to save costs and energy. A heuristic consisting of two phases is applied, combining the optimal job while respecting the queue of orders, the battery charging process, and the replacement schedule. Korth et al. (2018) describe an architecture model of a simulation-based digital twin for decision-making in intralogistics optimization. ERP systems act as the data basis. The model is intended to guide the planner and to generate partially automatic scenarios. The authors describe several potential areas of application, such as layout planning, technology selection, or order planning, in which the architecture model is conceivable. In a case study, the authors apply the model to optimize the shift planning of forklifts. Marinkovic et al. (2023) develop an architecture for a digital twin for optimal resource planning of internal transport systems. This is intended to improve decision-making in the planning and sequencing of transportation tasks of current and future scenarios.

In the field of selection of the optimal transport system in intralogistics, various MCDM approaches appear. The decision support systems of Chakraborty and Saha (2022), Fazlollahtabar et al. (2019), and Pamučar and Ćirović (2015) focus on selecting optimal forklifts based on criteria like the purchase price, age or working hours. Mahmutagić et al. (2021) develop a two-stage decision support system to evaluate the efficiency of the currently used forklifts and derive the optimal forklift selection based on this analysis. Zubair et al. (2019) solve an MCDM for a pharmaceutical company for selecting the optimal transport technology. Their solution approach includes a questionnaire to identify the state of the art. Then, an analytical hierarchy process is applied to choose between automated guided vehicles (AGV), conveyors, and forklifts. Rahnamay Bonab et al. (2023) support decision-making for the optimal selection of automated vehicles for freight transportation.

Coelho et al. (2021) develop a framework of a simulation-based decision support tool for the material supply of production plants. The work is intended to serve as the basis for a digital twin that can be used independently in various intralogistics scenarios. The data basis was partly collected manually, e. g. times for material handling by forklift. Kluska (2021) supports the decision-making process in the design of warehouse layouts and technical equipment.

A simulation model based on WMS data is used for this purpose. Constraints such as track widths for transport technology are considered. The planning is done automatically based on 17 steps. This automation significantly reduces the planning time compared to conventional planning.

In summary, it can be stated that various decision support systems exist for the material flow planning of internal transport systems. However, most systems deal with one-dimensional issues without holistic planning approaches. Thus, MCDM methods are used to evaluate and select manual and automated transport systems. Heuristics and simulations are used to optimize layouts and order allocation. Linear programming is very rarely used due to long calculation times. The data basis for the optimization methods usually comes from ERP or WMS systems. The data were sometimes generated using random numbers to test algorithms and procedures. The use of sensors to create real-time references is rarely applied. Therefore, some papers describe using sensors as one of the further research steps. This should enable the automation of material flow planning from data collection to decision-making, as data collection and processing currently causes high manual efforts.

3. Conceptual Decision Support System for Sensor-Based Material Flow Optimization

Based on the discussed related works, this section develops a concept of a decision support system for sensor-based material flow planning of internal transport systems in manufacturing companies. For this purpose, requirements, and restrictions for the decision support system are defined first. Based on these, the conceptual decision support system and its three layers are designed. Finally, the results are compared with the related works, and challenges for the transfer to public transport are discussed.

3.1. Requirements and Restrictions

The following requirements must be met when developing the decision support system:

- The planning content of the system shall include concept planning. For this purpose, weak points in the current material flow system are to be identified, optimization potentials are to be calculated and evaluated, and recommendations for action are to be derived and graphically prepared. This information is to be used by the company's management to determine the preferred scenario.

DOI: https://doi.org/10.30844/wgab_2023_2

- The decision support system shall perform material flow planning automatically from provisioning the required input data to the output of the optimization scenarios. System breaks are to be avoided to enable automated and continuous planning.

- The data basis for the decision support system should be collected as far as possible using sensors. This should create the necessary real-time reference and achieve independence from historical company data. Constraints will serve as additional data input if the needed data cannot be captured by sensors (planned production growth per year, etc.).

- The layout design, the material flow, the resource deployment of personnel and technology, and the examination of automation potentials are to be optimized. This is intended to create holistic planning of internal transport systems. Seasonality and growth scenarios are also to be integrated into the optimization procedure.

- The optimization steps should use operations research methods. Linear programming and heuristics will be used to identify weaknesses and calculate optimization scenarios. MCDM shall be used to weigh the constraints.

In addition to the requirements, limitations occur: Material flow systems consist of the components transport unit, transport technology, and transport organization (Martin 2016). The decision support system is intended to optimize the transport organization and to select the optimal transport technology. Optimization of the transport unit should not be executed. Load carriers with the dimensions of a euro pallet are assumed. The load factor of the forklift is defined with one pallet per transport for the current as well as for the optimized state. In addition, the transport technology is restricted to manual and automated forklifts. Only sensor data from manual forklifts will be used as data input. The area of application is to be limited to manufacturing companies. Material flows between goods receipt to production and production to goods issue shall be optimized. The storage technology used is a constraint considered, but it will not be optimized.

3.2. Conceptual Design of the Decision Support System

To achieve the objectives of this paper, a concept for an automated, sensor-based decision support system is developed that serves as a reference architecture. The structure of this conceptual decision support system is shown in Figure 1 and inspired by the structure of decision support systems described by Ben Rabia and Bellabdaoui (2022). It consists of three layers, which are discussed below.

- The data layer represents the interface to the input data. Sensor data is imported into the decision support system during the data collection function. In addition, the planning team defines constraints, which are also embedded in the system. The data processing function checks, prepares, and processes the collected sensor data. In the final step, the resulting data is stored in a database, which acts as an interface to the model layer.

- The analysis, calculation, and optimization logic are integrated into the model layer. Operations research methods are used to perform the functions assessment of constraints, weakness analysis, forecast, and optimization. The results of the model layer are identified weaknesses in the material flow and calculated optimization scenarios of the actual and target state under consideration of the defined constraints.

- The knowledge layer is used for supporting data-driven and efficient decision-making by the planning team. For this purpose, the solution evaluation assesses the planning results of the model layer qualitatively and quantitatively. The visualization graphically prepares all necessary information for the planning team. The report function documents the identified weaknesses and the calculated recommendations for material flow optimization.

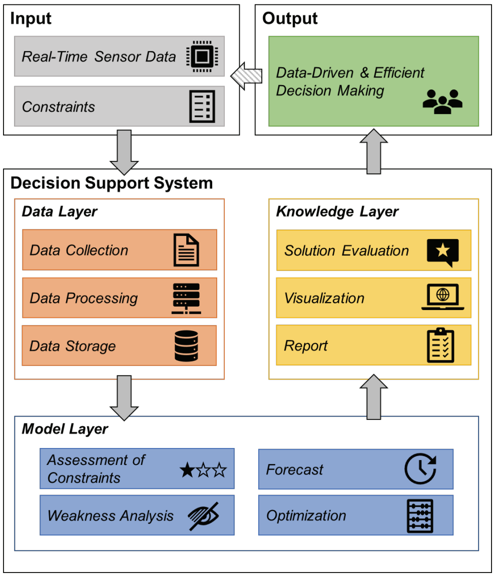

Figure 1: Concept of the decision support system

3.3. Data Layer

A holistic and up-to-date database is crucial for successful decisions in material flow planning. The collection, processing, and storage of this database is the task of the data layer. For this purpose, sensor data are defined that must be determined

DOI: https://doi.org/10.30844/wgab_2023_2

during data collection. Table 1 shows mandatory sensor data, relevant measured values, and required data type. Depending on the application, the table can be extended by further optional sensor data. For example, the ambient temperature in refrigerated warehouses may be of interest.

Real-Time Sensor Data	**Relevant Value**	**Data Type**
Timestamp	Time of reaching source/sink	DateTime
Travel time	Time interval in seconds between leaving the source and arriving at the sink	Integer
Handling time	Time interval in seconds between entering the source/sink and leaving the source/sink	Integer
Source	Starting point of the transport	String
Sink	End point of the transport	String
Route	Passed points and intermediate stops	String
Distance	Distance in meters of the traveled transport route	Integer
Loading condition	Loading condition of the forklift	Boolean
Lifting height	Maximum lifting height in meters performed during the transport	Integer
Transported weight	Maximum lifted weight in kg performed during the transport	Integer
Forklift vibrations	Maximum vibrations to which the forklift has been subjected	Integer

Table 1: Mandatory sensor data

Constraints are needed to guarantee realistic planning of the decision support system and must be defined by the planning team. On the one hand, these link the sensor data and the real world. A list of the currently used forklifts is used to assign the sensor ID to the means of transport. In addition, the type and the currently assigned function area must be defined. The position of the sources and sinks in the layout and their assignment to the sensor data must also be recorded by a list. Information on the space requirements, the use of the areas (production or warehouse), the material group concerned, and the type of transfer point (e. g. rack, conveyor system) must be defined. Information on the transport paths, such as width, gradient, indoor or outdoor use, and any mixed traffic must be provided.

On the other hand, data must be collected if it cannot be recorded using sensors. This includes data such as current shift schedules, secondary activities performed by forklift drivers, and the planned production volume growth in a defined planning horizon. In addition, a correction factor for seasonality should be specified if the sensor data was only collected temporarily. The constraints are concluded with a technology database that, according to VDI 2198 (2019), contains the core characteristics of current forklifts and automated guided vehicles. This database should be updated annually and not anew for each application. Microsoft Excel lists are provided for all these defined constraints, which can be automatically inserted into the decision support system. Figure 2 summarizes the required constraints. Mandatory constraints that must be fulfilled are indicated (M).

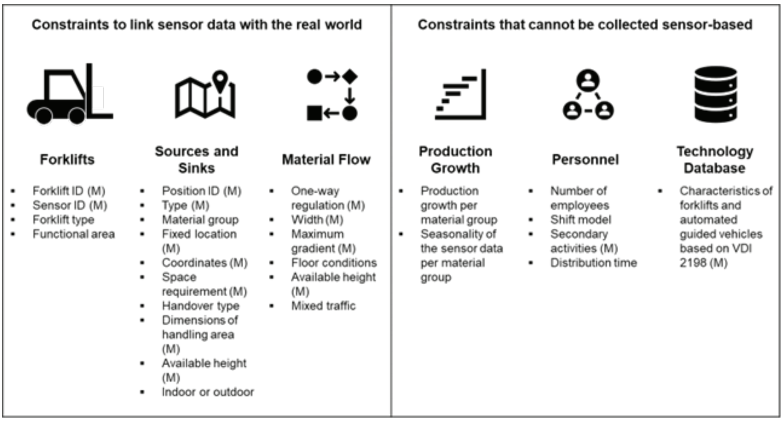

Figure 2: Required constraints of the DSS for material flow planning

After data collection, data processing takes place. First, the sensor data is checked for completeness and consistency. Incorrect sensor data are cleaned, duplicates are removed, and missing data records are added. Individual data records are combined to form integrated database entries. For this purpose, missing mandatory sensor data are calculated using other recorded data and defined formulas. For example, if the handling time is not recorded sensor-based, it can be determined by subtracting two consecutive time stamps and the measured travel time. If calculations are not possible, the planning team is informed that additional constraints are needed. For example, if the lifting height cannot be measured using sensors, the maximum lifting height required for each source and sink must be specified as an additional constraint.

Finally, the prepared data are stored in a database. It consists of the tables sensor-based material flow data, planning constraints, and technology database. These tables are the starting point for optimizing material flows in the model layer.

3.4. Model Layer

The model layer contains the optimization logic of the material flow planning and applies operations research methods during the functions assessment of constraints, weakness analysis, optimization, and forecast. Figure 3 shows, as an introduction, the optimization procedures, their results as well as the information flows between these procedures.

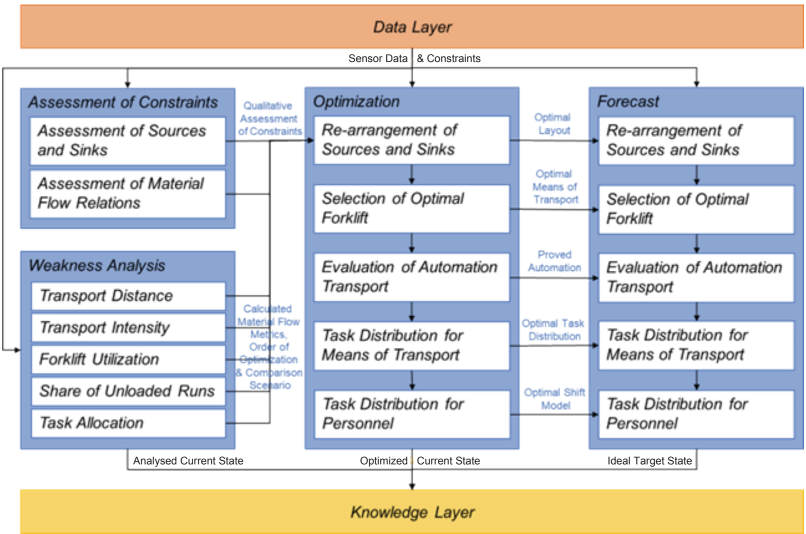

Figure 3: Structure of the model layer

First, the assessment of constraints function evaluates the optimal positions of sources and sinks and the quality of material flows using MCDM. The results are used to incorporate qualitative criteria into material flow planning during the optimization function. Both assessment procedures are described in the following.

The sources and sinks are evaluated using a pairwise comparison. Each position is seen as an alternative to every other position. Iteratively, the constraints of the original position are compared with the alternative position to be evaluated. Nine constraints for sources and sinks are used (see Figure 2, column 2). The following evaluation scheme occurs: If mandatory constraints are not fulfilled by the alternative position or less than four of the nine constraints are met, zero points are given. Zero points are also assigned if the source has the property fixed location. For example, a production line cannot be relocated. Therefore, all other positions in the layout are not suitable. If a maximum of six constraints are fulfilled, one point is awarded. Two points mean that a maximum of eight constraints are met. In the case that all constraints are fulfilled, three points are given. Four points are awarded if all constraints are met and at least one constraint is over-fulfilled compared to the original position, (e. g. an alternative has a more generous transfer area than the original position). The best score is five points if all constraints are met and at least three criteria are exceeded. After all, combinations have been evaluated, the results are documented in an evaluation matrix.

In the second step, the qualitative assessment of the material flow relations between the sources and sinks is done. For this purpose, the defined material flow constraints track width, maximum gradient, floor conditions, available height, and mixed traffic are evaluated. The actual constraints per transport relation are compared with the ideal condition using a pairwise comparison. The ideal transport route width is calculated based on the number of travel lanes incl. safety distances. In the optimal case, no gradients occur. The ideal ground conditions are without obstructions or damages, and suitable for automation according to VDI 2510 Part 1 (2009). Gates are usually limiting transport routes. In ideal conditions, there are no height limitations along the transport route. Ideally, there is no use of various transport vehicles or flows of people in the same area. In an iterative process, all occurring material flow relations are evaluated. The material flow relation receives one point for each criterion fulfilled. A maximum of five points per relation can be achieved. The results are documented in an evaluation table.

In addition, the weakness analysis function is used to analyze the actual situation of the material flow system based on the generated sensor data. This identifies the effort drivers that are to be eliminated during optimization. This is done by calculating material flow metrics such as traveled transport distances and intensities, forklift utilization, the share of unloaded runs, and task allocation per means of transport, per shift, and per hour based on the sensor data. The calculated key figures and the evaluated actual situation serve as a calculation basis for quantifying the optimization potential. Furthermore, the order in the optimization function is determined based on the weakness analysis. Critical challenges with high optimization leverage are optimized first, and non-critical conditions last.

The optimization function is based on the assessment of constraints and the calculated material flow metrics of the weakness analysis. The optimization procedure starts with re-arranging sources and sinks to minimize the transport intensities using a heuristic greedy algorithm.

DOI: https://doi.org/10.30844/wgab_2023_2

First, the algorithm places those sources and sinks with a fixed location assessment. The remaining sources and sinks are located to minimize the transport intensities. The number of actual outgoing material flows per position defines the order of this iteration process. The source/sink with the highest total transport load is placed first and the one with the lowest last. The algorithm places the source/sink on the alternative positions in the layout based on the evaluated suitability of the alternatives, which must have a rating of at least one point. The alternative positions with a high rating are prioritized, and positions with a low rating are avoided. The source/sink is rearranged until the cumulated transport intensities of all material flows arising so far result in a minimum. If several transport routes can be made, the qualitative evaluation of the material flows is considered. This is done if the difference in the transport distances of the variants deviates by a maximum of ten percent. In addition, the load on the transport network is calculated for each sub-route and considered in the selection of transport routes. The risk of bottlenecks and congestion is avoided by distributing the transport loads over different sub-routes although this can result in longer transport routes. If the position of the source/sink and the transport route is defined, the positioning of the next source/sink is continued. After all sources and sinks have been placed, the final calculation of the transport intensities of the optimized material flow is performed.

Once the transport intensities have been minimized, the optimal means of transport are selected for each task. A pairwise comparison is performed by comparing the properties of forklifts of the technology database with the constraints of the optimized layout. A forklift is considered suitable if it meets all mandatory constraints. Since various vehicle types can occur, the number of vehicles is limited to those that can be used in all or at least in most tasks in a second iteration step. This creates maximum flexibility and reduces the number of vehicle types.

In the next optimization step, the automation of the selected forklifts is evaluated. For this purpose, automated guided vehicles (AGV) are chosen if they correspond to the constraints of the re-arranged layout and the defined material flows. These constraints are evaluated in a pairwise comparison with the properties of the automated guided vehicles of the technology database. If all mandatory and optional constraints are fulfilled, a suitable AGV type is selected. During this evaluation, the mixed traffic, floor conditions, and outdoor use are of greater importance than in selecting forklifts since these constraints strongly limit AGV use.

In the following optimization step, the transport tasks of the material flows are distributed to the selected transport systems to determine the optimal number of vehicles. This is done by assigning transport orders to forklifts in the sequence of the sensor-based detected time stamps using a greedy algorithm. The duration of the transport order is calculated by the sensor-based collected handling and driving times. If the forklift type is changed compared to the currently used forklift, a correction factor is considered to account for the different characteristics. Furthermore, the defined distribution times are integrated. When placing transport orders, an iterative approach is taken in two phases. In the first phase, the current function assignment of the forklifts is considered in the task allocation. In the second phase, no function allocation is considered. This should minimize the share of empty runs. In both phases, forklifts are chosen if their characteristics correspond to the transport order based on the selection procedure performed. For the following transport orders, an additional forklift is needed if the already chosen forklifts are already executing transport orders or do not meet the order specifications. This is done until all transport orders have been assigned to forklifts. Afterward, the utilization of each forklift is analyzed. For forklifts with low utilization rates below 50 percent, an attempt is made to transfer the transport load to other forklifts of the same type. This is done by slightly varying the time stamps and the defined distribution time. After both phases (with and without functional area assignment) have been executed, the results are compared. The phase with the lower number of means of transport is used for optimizing personnel deployment.

To distribute workloads among personnel in a socially even and balanced manner, an optimized shift schedule for forklift drivers is created. For this purpose, the forklifts are grouped so that the shifts can be optimally staffed. Each group is assigned to an employee who executes the orders of the assigned forklift pool. In the first step, planning is done with predefined shift models. In the second step, an ideal creation of a new shift model takes place. In both cases, the task allocation considers required secondary activities. Finally, the required employee capacities per phase are compared to determine the optimal variant.

The forecast function integrates the targeted company growth in a defined planning horizon into the optimization procedure. In addition, the generated sensor data is adjusted for seasonal fluctuations, for example, to avoid variations due to the limited availability of sensor data. Transport orders are automatically generated and added to the sensor-based collected database to account for growth and seasonality. This supplemented data includes the addition of production lines or the acceleration of the production cycles of the current production lines depending on the given constraints. Through these additional data sets, the target state is achieved, which is optimized using the described methods of the optimization function.

The results of the model layer, the analyzed weaknesses of the actual state, and the optimized actual and target state are finally transferred to the knowledge layer.

3.5. Knowledge Layer

The knowledge layer is developed for knowledge transfer to the planning team. First, the scenarios calculated by the model layer are evaluated in the solution evaluation function regarding their technical feasibility. This is done by checking if the defined constraints are met. In addition, optimization potentials are to be evaluated quantitatively. For this purpose, the savings of transport intensity, resource usage,

DOI: https://doi.org/10.30844/wgab_2023_2

time, and cost savings are calculated compared to the actual situation. A sensitivity analysis is done to consider the influence of the selected methods and constraints on the results. The results of the solution evaluation and those of the model layer are graphically prepared for the planning team using the visualization function. This includes the visualization of the calculated layout variants, sankey diagrams, distance-intensity matrices, and shift plans for the current state, the optimized current state, and the optimally designed target state. The report function serves as a written summary of the planning results. It contains a chronological list of recommended actions to achieve the optimal target state for each planning step.

All these reports and diagrams are provided for the planning team. Complex planning problems are presented. Thus contribute to an efficient and data-driven decision-making process for optimizing internal material flows. The analyzed actual state shows the planning team the weaknesses of the current material flow system. The optimized actual state supports achieving short-term efficiency improvements. The result of the optimized target state provides recommendations for action to handle the planned company growth in intralogistics. If alternative scenarios are still to be considered, the data input of the constraints can be revised, and the automated planning of the decision support system can be started again. In addition, further sensor data can be integrated into the model to expand and optimize the planning results. This process can be iterated until all relevant scenarios have been examined, and an optimal decision can be made.

3.6. Discussion of results

During this section, a decision support system for internal material flow planning was designed. This system combines operations research methods to create a holistic planning and optimization of material flows executed by forklifts. Compared to related works in section 2, which deal with one-dimensional planning problems, multidimensional challenges of material flow planning (source/sink arrangements, deployment of resources/personnel, and automation potentials) can be solved.

The need for using sensors and their real-time data basis is highlighted in related works as an urgent need for research. Estanjini et al. (2010) provided a decision support system based purely on sensor data for optimizing the use of forklifts. Combined with the previously discussed multidimensional solution approach, a significant contribution to the state-of-the-art could be made during this contribution. The real-time reference of this conceptual decision support system improves the optimization results of standard operations research methods. In addition, it prepares decision-making efficiently and based on actual data. To ensure sufficient quality of the sensor data, supporting procedures for the selection and use of optimally suited sensors should be considered in future works.

The modular structure and the designed algorithms of the conceptual decision support system enable the automation of the planning steps of material flow concept planning from data collection to the preparation of recommended actions.

This creates an increase in efficiency and a reduction in planning times compared to the state of the art. The manual collection of the needed constraints is still an exception. Future research should focus on automating the determination of planning constraints (e. g. automated identification of track widths from plant layouts). In summary, it can be stated that the conceptually designed, sensor-based decision support system exceeds the state-of-the-art and fulfills all requirements defined in section 3.1.

3.7. Discussion of challenges of the transfer to public transport

This contribution aims to transfer the conceived, internal decision support system to public transport. In advance, potential challenges that prevent a transfer will be discussed before the concept is transferred in section 4. As in intralogistics, public transport is a material flow problem to get the right object to the right place at the right time in the right quantity and quality at minimum cost. Therefore, a transfer of intra-logistics concepts to public transport can be concluded. Due to some possible differences in specific use cases, challenges may arise that prevent a transfer. The conceptually designed decision support system is limited to internal forklift transports. During public transport, analogies to milk run systems in the industry, which are generally not implemented using forklifts, occur in the case of bus or tram transports. The fundamentally different logic of milk runs could cause limitations during transfer. The application area in section 4 is the implementation and evaluation of crowdsourcing delivery using tramways in Vienna to create sustainable, intra-city parcel delivery on the last mile. The focus of the conceptual decision support system is techno-centric and economic. The consideration of sustainability criteria is currently not considered. This lack of sustainability aspects can also make transfer difficult. Finally, the data basis and structure are designed for using sensors on internal forklifts. Other sensors will be used in public transport. In addition, different sensor data will serve as data basis. Needed adjustments to this new data structure can also prevent a transfer. In public transport, significantly higher requirements are to be assumed regarding data security, handling of personal data, and legal aspects. Restrictions can also arise due to these factors.

4. Transfer to Public Transport

Challenges arise not only in the internal but also in the external material flow due to shorter delivery times and increasing e-commerce. In particular, the sustainable and efficient delivery of parcels on the last mile is currently not possible. Crowdsourcing delivery is seen as a solution to this challenge. The concept of crowdsourcing delivery implies the delivery of parcels by a network of individuals who deliver them along their routes using underutilized resources (Ciobotaru/Chankov 2021). Data-driven research on the transport routes of passengers, means of transport, and goods to quantify the potential of crowdsourcing delivery in public transport has not yet been done.

DOI: https://doi.org/10.30844/wgab_2023_2

Due to the resulting lack of data-based decision-making, this is one of the reasons why crowdsourcing delivery has not yet become established (Le et al. 2021; Yildriz 2021).

The Öffi-Packerl research project is currently addressing this research gap. This project aims to use unused transport capacities of Viennese tramways for parcel deliveries on the last mile. This shall be achieved by the concept of crowdsourcing delivery, where passengers act as transporters of parcels. Therefore, prototypes of a mobile smartphone app that serves as a transport management platform and associated, autonomous parcel stations at tramway stops are to be developed. Figure 4 shows the concept of the Öffi-Packerl project based on these prototypes.

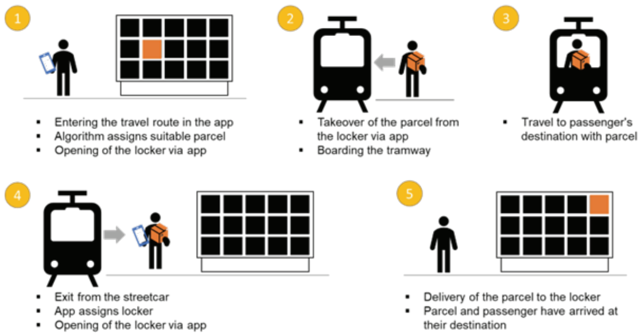

Figure 4: Concept of the Öffi-Packerl research project

By implementing these prototypes, data will be collected for the first time to quantify the potential of crowdsourcing delivery in public transport. This will serve as a basis for decision-making on implementing this concept in Vienna. For example, the decision-making process includes the stops suitable for parcel stations due to space restrictions or relevant tramway lines regarding passenger numbers. For this purpose, Figure 5 shows to what extent the decision support system can be transferred to the Öffi-Packerl project.

The data layer can be transferred almost unchanged to the Öffi-Packerl project. The sensor data will mainly be GPS data, for example, to evaluate the duration of transfers with pickup or placement of a parcel. In addition to the sensor data, app data will occur in real time. These must be additionally integrated into the data processing and storage. Since personal data is recorded using the app, higher data protection guidelines come into force as a supplement. Secure encryption of the data must be ensured. The assessment of constraints function can be applied unchanged to public transport. The assessment of sources and sinks in intralogistics is used for assessing public transport stops. The assessment of material flow relations corresponds to the assessment of tramway lines. The weakness analysis still calculates the required transport metrics, but the analysis for weaknesses is not required. The other functions of the model layer need to be adapted. The algorithms for task distribution of forklifts and personnel of the optimization function can be seen as a basis for the matching algorithm of passengers, parcels, and tramways. However, a specific further development to the concrete challenges of Öffi-Packerl is necessary. The optimization of the transport routes of the packages in the public transport network can be done based on the algorithm for layout optimization. The selection of suitable manual and automated transport systems is not considered relevant for the Öffi-Packerl project. The forecast function shall continue to optimize target states. This is done based on the adapted algorithms of the optimization function. The tasks of the knowledge layer functions remain unchanged compared to intralogistics. Only the creation of higher data security must also be considered.

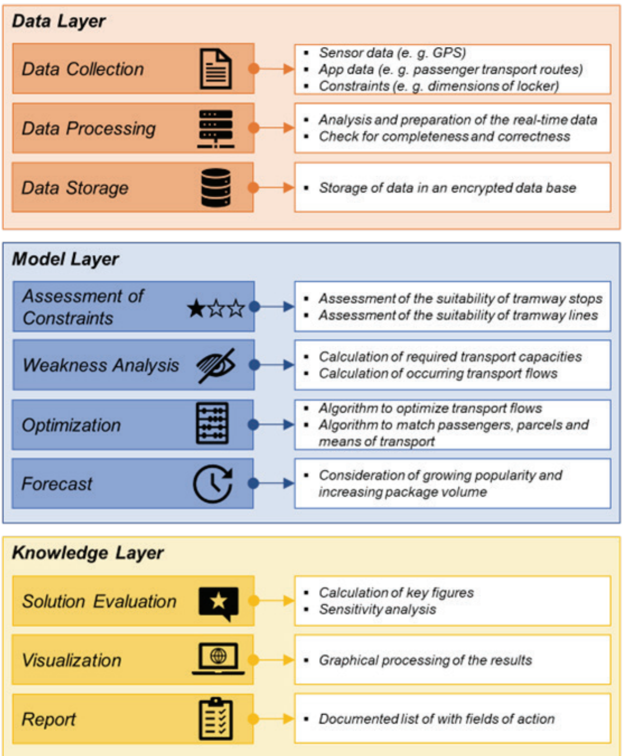

Figure 5: Transfer to crowdsourcing delivery in public transport

In summary, it can be stated that the developed internal decision support system can significantly contribute to the Öffi-Packerl research project. The transferability to public transport and in particular to crowdsourcing delivery is shown. This

DOI: https://doi.org/10.30844/wgab_2023_2

demonstrated that in-plant methods such as operations research can contribute to sustainability outside of industrial use cases. The expected challenges in section 3.7 that might prevent transfer can thus be disproved, although significant adjustments must be made, especially in the model layer and its algorithms.

5. Conclusions

In this contribution, a decision support system has been conceptually designed. This system enables holistic, realistic, data-driven, and efficient material flow planning of internal transport systems based on operations research methods. The data basis is collected by sensors and required constraints are defined. The structure of the decision support system consists of three layers: data, model, and knowledge layer. The data layer collects, prepares, and stores the required database. The model layer integrates logic and algorithms to analyze, evaluate and optimize material flows, source and sink arrangements, deployment of resources and personnel, and automation potentials of forklifts. The knowledge layer prepares the planning results in an easily understandable way and thus enables efficient and data-driven decisions by the planning team. This decision support system exceeds the state-of-the-art due to the consideration of multidimensional planning problems of internal transport, the real-time reference through the integration of sensor data, and the automation of material flow concept planning from data collection to the derivation of recommended actions.

Since similar challenges arise in the application of crowdsourcing delivery, the transferability of the developed concept to public transport was evaluated in the Öffi-Packerl research project. It was demonstrated that the discussed decision support system can be transferred to public transport. For this purpose, the model layer and its algorithms must be adapted. The data and knowledge layer can be transferred almost unchanged. This paper shows that expected challenges that prevent a transfer could be disproved and industrial management methods can contribute to a sustainable future outside of factories.

Further research concerns the selection of suitable sensors and the integration of these into the decision support system. In addition, sustainability criteria will be integrated into decision support for material flow planning. Furthermore, the concept should be transferred into a software demonstrator for decision support in material flow planning. This demonstrator should be applied in case studies at manufacturing companies in different industries to quantify the added value compared to conventional methods of material flow planning.

Acknowledgements

The Öffi-Packerl project is funded by the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation, and Technology as part of the program Mobility of the Future, grant no. 897312, and is managed by the Austrian Research Promotion Agency FFG.

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MTM in Motion – Perspectives to Digital Work Design

Deriving MTM Analyses from Virtual Reality Tools

Peter Kuhlang, Martin Benter, Maria Neumann

1. Introduction

The cost of production is a key competitiveness factor for industrial companies in national and international markets. Labour costs are one relevant portion of these costs, especially for production sites with a high percentage of manual processes. Therefore, describing, analysing, and designing manual work processes in a systematic way is an important task in most Industrial Engineering departments. By mastering this task and designing productive and healthy workplaces, companies can reduce the cost of production and make sure that the time of their employees is used for meaningful activities.

There are multiple methods to describe and analyse work processes. Widely known methods to assess process times include REFA (REFA 1997), MTM (Antis et al. 1969; Bokranz/Landau 2012; Maynard et al. 1948) and Work Factor (Quick 1960). While there are multiple MTM methods to address the different types of production, one of the most established methods is the process building block system MTM-UAS® (MTM-Universal Analysing System; Bokranz/Landau 2012; MTM 2019).

The most recent process building block system is Human Work Design (MTM-HWD®, Finsterbusch 2016; Finsterbusch et al. 2019). It describes work processes not only from a productive standpoint, but also includes ergonomic factors to assure productive and ergonomic work in one step.

While the MTM systems can be used to systematically design work processes, they still require manual effort for data collection and interpretation of the method user. Due to this fact, not every company has the capacities to design work using MTM systems. One possibility to reduce this effort is the automatic interpretation of digitized human motion data.

DOI: https://doi.org/10.30844/wgab_2023_3

Motion data depicts human movements and postures and includes, for example, distances covered, joint positions or object interactions. One technology that is capable to generate this data is virtual reality. Thanks to the advances in the technology in recent years, it can be used in a variety of workplaces and with minimal training.

2. The process language MTM and the process building block system MTM-UAS®

The process language MTM and its different process building block systems like MTM-1®, MTM-UAS® and MTM-HWD® are characterized by their own syntax and semantics. They provide the vocabulary and the grammar to describe work processes in a standardized and understandable way (Antis et al. 1969; Bokranz/Landau 2012; Kuhlang 2018; Maynard et al. 1948).

The notation of each MTM process building block is characterized by several language elements (Antis et al. 1969; Bokranz/Landau 2012; Kuhlang 2018; Maynard et al. 1948). The code is the "name" or designation of a process building block. For example, the code *KA* in MTM-UAS® describes the movement of the trunk. It is also characterized by a defined beginning, description and ending. The building block *KA* begins when the trunk starts to move and ends when the target location has been reached. In other MTM systems, walking is indicated by corresponding codes. In MTM-1, for example, this would be a W (walk, MTM-1 2019; MTM-UAS 2019). The language elements also include the influencing factors that further describe each process building block (MTM-1 2019; MTM-UAS 2019). These factors generally include accuracies, distances, postures, and forces (Benter/Kuhlang 2019; Benter/Kuhlang 2021). In the example of walking, the most important influencing factor is the travelled distance.

In addition to these descriptive language elements, each process building block has an evaluated standard time value. For instance, the process building block *KA* has a standard time of 25 TMU (Time Measurement Units, 25 TMU equal approximately 0.9 seconds). These times are globally standardized and widely accepted in multiple industries (i.e., automotive, or white goods). By describing the whole work process with corresponding process building blocks, the entire required time for that process can be calculated (MTM 2019).

Motion Length in **cm**	≤ 20	> 20 to ≤ 50	> 50 to ≤ 80
Distance Class	**1**	**2**	**3**

Get and Place			**Code**	**1**	**2**	**3**
				TMU		
	Case of Get	Case of Place				
≤1 kg	easy	approx.	**AA**	20	35	50
		loose	**AB**	30	45	60
		tight	**AC**	40	55	70
	difficult	approx.	**AD**	20	45	60
		loose	**AE**	30	55	70
		tight	**AF**	40	65	80
	handful	approx.	**AG**	40	65	80
> 1 kg to ≤ 8 kg		approx.	**AH**	25	45	55
		loose	**AJ**	40	65	75
		tight	**AK**	50	75	85
> 8 kg to ≤ 22 kg		approx.	**AL**	80	105	115
		loose	**AM**	95	120	130
		tight	**AN**	120	145	160

Place		**Code**	**1**	**2**	**3**
			TMU		
	approx.	**PA**	10	20	25
	loose	**PB**	20	30	35
	tight	**PC**	30	40	45

Motion Length in **cm**	≤ 20	> 20 to ≤ 50	> 50 to ≤ 80
Distance Class	**1**	**2**	**3**

Handle Tool	**Code**	**1**	**2**	**3**
		TMU		
approximate	**HA**	25	45	65
loose	**HB**	40	60	75
tight	**HC**	50	70	85

Operate	**Code**	**1**	**2**	**3**
single	**BA**	10	25	40
compound	**BB**	30	45	60

Motion Cycles	**Code**	**1**	**2**	**3**
one motion	**ZA**	5	15	20
motion sequence	**ZB**	10	30	40
re-position and one motion	**ZC**	30	45	55
tighten or loosen	**ZD**	20		

Body Motions	**Code**	**TMU**
Walk / m	**KA**	25
Bend, Stoop, Kneel (incl. arise)	**KB**	60
Sit and Stand	**KC**	110

Visual Control	**VA**	15

Figure 1: MTM-UAS® Data Card Basic Operations (MTM 2019)

Figure 1 shows the process building blocks (here: basic operations) for MTM-UAS®. Their building blocks are divided into *Get and Place*, *Place*, *Handle Tool*, *Operate*, *Motion Cycles*, *Body Motions* and *Visual Control*. The Figure also shows the relevant influencing factors for these basic motions like the *Distance Class* or *Case of Place*.

3. Digital technologies and the need to develop MTMmotion®

Digital technologies are increasingly finding their way into all aspects of the working world. In the field of work design, this includes, among others, technologies that generate or record human movement data and then process it further. These include human simulation (e.g., ema Work Designer: imk 2023; Fritzsche et al. 2019), virtual reality (e.g., LIVINGSOLIDS 2022 or halocline 2023) and motion capture (e.g., XSens: Movella 2023).

With these technologies, human work can be designed in a targeted manner, especially if the work processes under consideration are systematically evaluated in terms of time and ergonomics. Classic methods of work design such as MTM and REFA (see chapter 1) are suitable for this.

For example, the software manufacturer imk has developed a solution for deriving MTM analyses from the human simulation tool ema Work Designer and evaluated it in cooperation with the MTM ASSOCIATION e. V. (Fritzsche et al. 2019; Benter/Kuhlang 2021; imk 2022).

DOI: https://doi.org/10.30844/wgab_2023_3

In addition to imk, other technology manufacturers are also interested in such solutions. MTMmotion® was developed to ensure that the developed solutions deliver valid, rule compliant MTM analyses and that all technologies have equal access to the MTM systems. Figure 2 illustrates this approach.

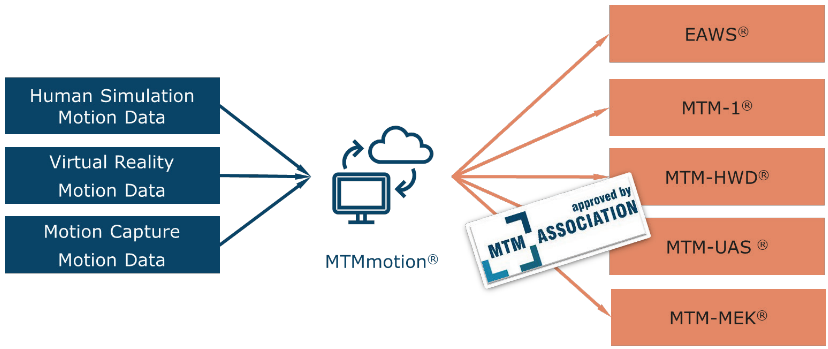


Figure 2: MTMmotion® – Technology independent MTM translation

MTMmotion® aims to act as an interface through which human movement data is translated uniformly (for all technologies) into correct MTM analyses. The integration of MTM enables technology users to carry out a targeted analysis and design human workplaces. It also fulfils the statutory mandate of the MTM ASSOCIATION e. V. to further spread the MTM methods, to ensure their correct application and it is awarded by the certificate "approved by MTM ASSOCIATION".

4. Exemplary workplace

An exemplary workplace will be used to demonstrate the interface data as well as the results of the translation algorithm. In the given example the worker preassembles a module for a dish washing machine, which consists of a component carrier, two pumps, several hoses, screws, and other small parts. The assembly time of the complete workflow takes about 2 minutes, but this article focuses one of the last steps of the process, which is fastening the pumps with screws.

The whole workstation including all the necessary processes were modelled in a virtual reality (VR) tool developed by the company LIVINGSOLIDS (LIVINGSOLIDS 2022). This VR solution uses a VR headset and handheld controllers. To record the body motions, it also uses marker-based motion capture cameras. This VR setup was used to assemble the product in the virtual reality application.

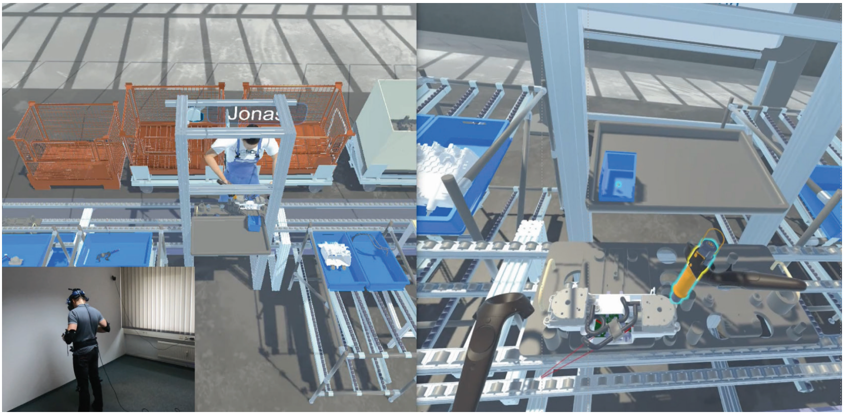


Figure 3: Views of the LIVINGSOLIDS virtual reality tool

Figure 3 shows several images of the software and the user while creating the recording. In the lower left, one can see the worker wearing the VR components. Above this is the central view of the software, while the right side shows the view of the worker. In the shown moment, the worker is assembling a screw using an electric screwdriver, which can be seen in the right picture.

5. Derivation of MTMmotion® data

5.1. General approach of MTMmotion®

The translation of the data generated by the VR software is realized by using MTMmotion®. At its core it consists of two elements. One element is a digital language to describe human work processes or a motion data interface. The other element are algorithms that translate the interface data into valid MTM analyses. The concept is illustrated in Figure 4.

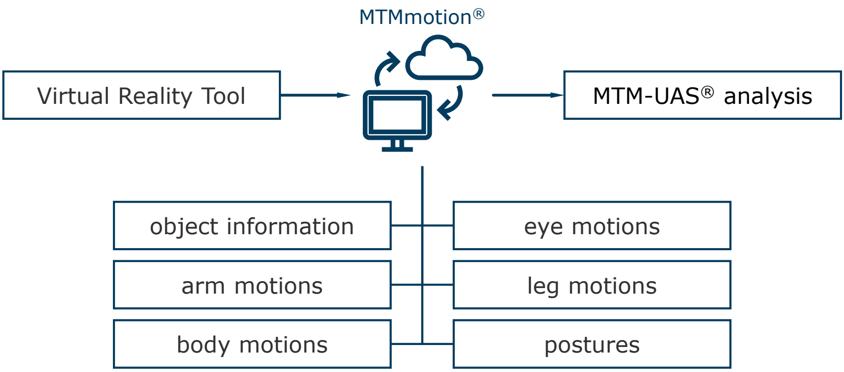


Figure 4: Derivation of MTM-UAS® analyses form VR tools using MTMmotion®

DOI: https://doi.org/10.30844/wgab_2023_3

The interface describes digital motion data in a way that allows digital tools like the VR solution by LIVINGSOLIDS to deduce that data from their own inherit data structure. It also consists of all the necessary information to derive valid MTM analyses. The data structure is described in chapter 5.2. The deduction of the interface is different for each technology or software as their data architecture is different as well. In the shown use case, the algorithms to fill the interface were developed by LIVINGSOLIDS and tested in cooperation with the MTM ASSOCIATION e. V.

If a VR tool like LIVINGSOLIDS delivers the motion data to the MTMmotion® interface, the data is translated into valid MTM analyses. This process is described in detail in chapters 0 and 7.

5.2. MTMmotion® interface data

The interface consists of an object list and six motion channels that describe human work processes. The interface channels generally describe data over time. In this context, the data in these channels contain information about movements and postures. The object list and the channels are filled with all the relevant data needed to describe the movements and postures performed by an employee when executing a work task as well as the objects with which they interact.

The interface is structured as follows:

1. Object List
2. Channel Body Motions
3. Channel Arm Motions
4. Channel Leg Motions
5. Channel Eye Motions
6. Channel Body Postures
7. Channel Arm Postures

The Object List describes the objects being handled by the worker and their relevant values such as weight or measurements for a more specific description of the object. The Motion Channels (Body, Arm, Leg and Eye) describe the movements that are performed by the worker. The other two channels depict the posture of the worker during their work task. For the example workplace, the channels Object List and Arm Motions are crucial and will be shown in detail. They also represent the most relevant information for manual work tasks in general.

object ID	object type	weight [kg]	dimensions [mm]	flexible
1	screw	0.02	5 x 12 x 12	no
2	screwdriver	1.2	150 x 50 x 80	no
3	hose	0.2	10 x 10 x 100	yes

Table 1: MTMmotion® data – object list

Various object information is needed for the derivation of an MTM analysis (see Table 1). *Weight*, *Height*, *Width*, and *Length* describe the physical properties of the object. In general, the larger or heavier an object is, the more difficult it is to handle and thus, the MTM standard time is higher. *Flexible* is another physical property that can make the handling of the object challenging. The table shows the three objects that are used for the presented steps of the process: Screws, hoses, and a screwdriver to assemble the screws and hoses, as well as an excerpt of their most relevant object information.

time start	time end	object ID	side	arm motion	supply	usage type
51.0	51.5	2	right	ObtainObject	separated	-
51.5	52.5	2	right	MoveObjectTo OtherPosition	-	-
52.5	56.8	2	right	HoldObject	-	-
52.6	53.6	1	left	ObtainObject	clustered	-
53.6	54.4	1	left	MoveObjectTo PointOfUse	-	-
54.4	56.8	1	left	UseObject	-	place
56.8	57.8	2	right	MoveObjectTo PointOfUse	-	-
57.8	61.7	2	right	UseObject	-	screw in

Table 2: MTMmotion® data – arm motions

Table 2 shows the necessary information for the channel Arm Motions. An essential aspect of these motions is the type of movement (*motion*) with which the employee performs their tasks. They can be distinguished by whether an object is obtained, moved, used, or held. Additionally, the motion type *UseObject* can be differentiated further by the *Usage Type*, because for most objects there are different ways to use the object. A screw could – at its point of use – be screwed in or inserted or just placed on a screwdriver tip.

In the example workplace the worker first obtains the screwdriver, which hangs in a separated position, with their right hand and moves it into the main working area. They then hold the screwdriver in position while they are picking up a screw

DOI: https://doi.org/10.30844/wgab_2023_3

out of a box full of screws with their left hand. They bring the screw to the screwdriver (point of use) and place the screw on the screwdriver. Lastly, they move the screwdriver (with screw) to its point of use (the pump) and screw in the screw.

Each arm motion is further specified by various additional influencing factors to describe the individual movement of the employee. For example, it is relevant which arm (*side*) performs the movement. To understand the workflow, it is also vital to track the start and end time of the movements. This helps to follow the chronological sequence of operations as well as to determine if arm movements are simultaneously performed with movements of other body parts.

In addition to the influencing factors that are important for all arm motions, there is also motion specific information, which is shown in Table 3.

	Distance	GraspType	Supply	Tolerance	Symmetry	Force	Process Time
Type	numeric	selection	selection	selection	selection	numeric	numeric
Unit	cm	-	-	mm	-	Newton	seconds
decimal points	1	-	-	-	-	1	2
required/ optional	optional	optional	optional	optional	optional	optional	optional

Table 3: MTMmotion® data – influencing factors of the arm motions

Distance is the actual motion path taken, which is generally arched and measured in centimetres. For hand motions the base knuckle of the index finger is used as a measuring point to determine the distance. For finger motions the fingertip is used as a measuring point. The *GraspType* describes the posture of the hand when gaining or relinquishing control over an object. *Supply* refers to the arrangement or position of the object before it gets grasped. The *Supply* types differ in the way an object is provided: fixed location (e.g., a button), varying location each work process (e.g., tools) or jumbled with other objects of the same kind (e.g., screws).

Tolerance describes the maximum ± deviation from the Point of Initial Engagement and is used to specify the required place accuracy. There is a selection of five different tolerance ranges given which are specified in millimetres. *Symmetry* refers to the symmetry condition of the positioning process. There are two options of symmetry given to the user: either the object does not need orientation for the positioning process (e.g.: placing a nail on a wooden board) or it does need orientation (e.g.: placing a screwdriver on a screw).

Force describes the required force to move or position an object. It stands for the physical force exerted by the body and effects the object that needs to be moved or positioned. It is measured in Newton and can be entered by the user. *ProcessTime* is the time of a specific process that can be calculated through estimation, time study or by using self-activated recording instruments (e.g., time recorder).

It can represent the operating time of a tool or machine, for example, the screw process of an automated screwdriver or the press time of a press. *ProcessTime* is measured in seconds and is also an optional influencing factor.

6. Translation into MTM-UAS® analyses

The translation of the interface data into valid MTM analyses is the second part of the approach. This process is divided into the following process steps, which will be described in detail in the following sub-chapters:

1. Input data validation
2. Input data completion
3. Translation into process building blocks
4. Combination of different body parts

6.1. Input data validation

Firstly, the algorithm validates the input data supplied by the virtual reality tool. It checks whether the input data is meaningful or if it contains logical flaws. This means for instance that it checks if the handling of objects follows a meaningful order. Figure 5 shows a part of the validation algorithm. Here, the algorithm would detect an error if objects were moved that were not obtained before. In those cases, the object section, which includes all motions done with the same object in a sequential order, is deleted.

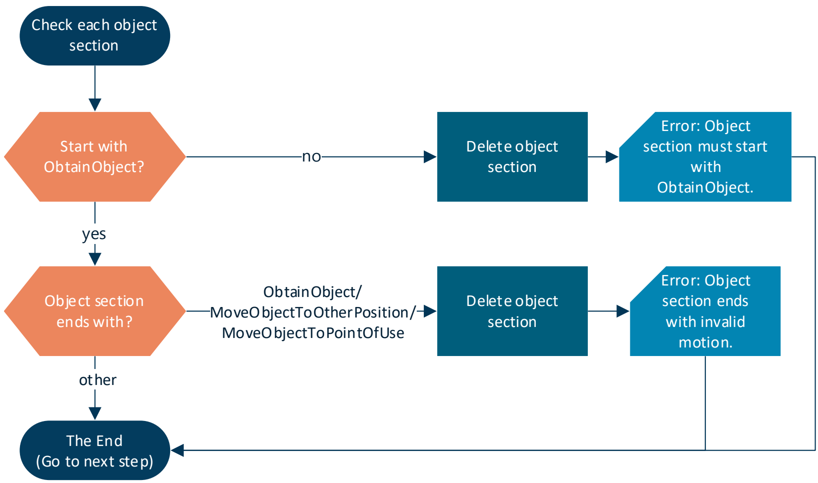


Figure 5: validation of object sections

DOI: https://doi.org/10.30844/wgab_2023_3

Additionally, the algorithm checks if the handling of an object ends with an invalid motion such as *ObtainObject* or *MoveObjectToPointOfUse*. Those motions are only a part of a meaningful object handling if they are followed by other motions like *UseObject*. In case the following motions are missing, the object section is deleted, and an error is issued. The given exemplary workplace can be used to explain this in detail (view Table 4). If the arm motion *ObtainObject* is missing for the screw (row 4, objectID 1), the meaning of the complete object section (rows 5-6) is unclear and thus deleted and not further used for translation.

time start	time end	object ID	side	arm motion
51.0	51.5	2	right	ObtainObject
51.5	52.5	2	right	MoveObjectTo OtherPosition
52.5	56.8	2	right	HoldObject
53.6	54.4	1	left	MoveObjectTo PointOfUse
54.4	56.8	1	left	UseObject

Table 4: missing arm motion for screw (objectID 1)

There are other queries the algorithm uses to check if the data provided by the user is conclusive. This article, however, does not aim to explain the whole algorithm, but focuses on a few examples to show how the translation works in general.

6.2. Input data completion

In the next step, the algorithm checks whether the input data is complete (view Figure 6). Although the interface contains all the information that is needed for a complete MTM analyses, it is not necessary to put in every non-essential information. First, the algorithm checks whether the used object exists in the provided object list. If that's not the case, a standard object replaces the unknown object, and an error is issued. The system cannot process an object that it is not familiar with. Then, missing information is filled with standard data. For example, the algorithm would add an average screw weight if it wasn't given by the VR tool. This step does not only apply for object data but also for all the motions and postures in the interface. For example, for all arm and leg motions except *UseObject* the standard value for distance is 40 centimetres. The Standard distance for *UseObject* is filled for each *UsageType* individually.

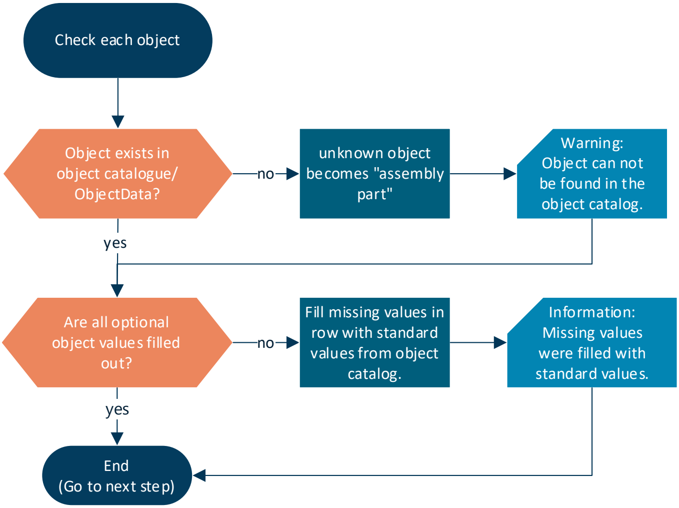


Figure 6: validation of object information

6.3. Translation into building blocks

One very important step of the algorithm is the translation of the various motions into MTM process building blocks. In the case of MTM-UAS®, it is often necessary to combine certain motions to basic operations (see Figure 1). However, each one of those combined motions supplies relevant data that is used to determine the right MTM-UAS® code.

<table>
<tr><th>object ID</th><th>side</th><th>arm motion</th><th>Basic Operation</th><th>CaseOfGet</th><th>CaseOfPlace</th></tr>
<tr><td>2</td><td>right</td><td>ObtainObject</td><td rowspan="3">Handle Tool</td><td>> 1 kg to < 8 kg</td><td>-</td></tr>
<tr><td>2</td><td>right</td><td>MoveObjectTo OtherPosition</td><td rowspan="2">-</td><td rowspan="2">approximately</td></tr>
<tr><td>2</td><td>right</td><td>HoldObject</td></tr>
<tr><td>1</td><td>left</td><td>ObtainObject</td><td rowspan="3">Get and Place</td><td>≤ 1 kg, difficult</td><td>-</td></tr>
<tr><td>1</td><td>left</td><td>MoveObjectTo PointOfUse</td><td rowspan="2">-</td><td rowspan="2">loose</td></tr>
<tr><td>1</td><td>left</td><td>UseObject</td></tr>
<tr><td>2</td><td>right</td><td>MoveObjectTo PointOfUse</td><td rowspan="2">Place</td><td>-</td><td>tight</td></tr>
<tr><td>2</td><td>right</td><td>UseObject</td><td>-</td><td>-</td></tr>
</table>

Table 5: translation of arm motions into interim result with basic operations

DOI: https://doi.org/10.30844/wgab_2023_3

That's why a first step in the translation into MTM-UAS® is the determination which motions are part of a basic operation. Table 5 shows the arm motions and their corresponding basic operations (column 4).

In the next step the influencing factors are deduced. For MTM-UAS® the *CaseOfGet* and the *CaseOfPlace* are central factors. The value *CaseOfGet* describes the way an object is obtained. This can vary from a simple obtain of a light object such as a screw to the difficult task of gaining control over a heavy box that weights 10 kg. These factors are calculated using the data of the object list as well as the arm motion data. For the exemplary workplace the influencing factors *CaseOfGet* and *CaseOfPlace* can be viewed in Table 5.

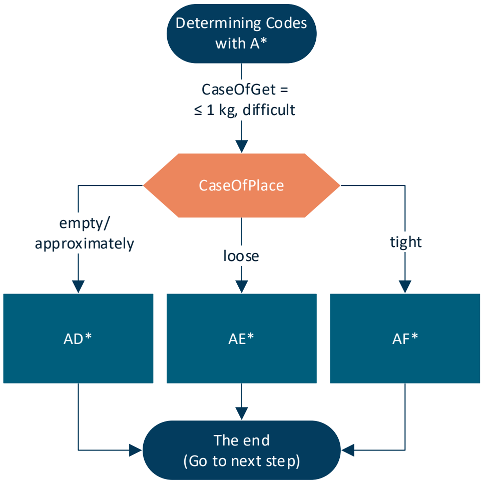


Figure 7: extract of the translation of Get and Place

Finally, the influencing factors are used to determine the correct code. A part of the algorithm to realize that step is shown in Figure 7. With the given influencing factors for the *Get and Place* of the screw (Table 4, rows 4-6; *CaseOfGet* ≤ 1 kg, difficult and *CaseOfPlace* is loose) the MTM-UAS® Code AE* is translated.

6.4. Combination of different body parts

The last step of the algorithm compares each Channel with motions with the other Channels to check if they influence each other or if there are motions performed at the same time. A very clear example for the influence of one channel on another is when a body motion is followed directly by an arm motion.

One of the MTM rules states that part of the arm motion can be performed during the body motion and thus the remaining effective distance of the arm motion is 10 cm. This rule is checked and realized in the MTMmotion® algorithm.

The MTM rules are also applied to check if motions can be performed simultaneously in industrial workplaces. For example, the algorithm would check if the screw can be obtained and placed, while the other hand holds an object like the screwdriver. In that case, this does not result in a conflict. In contrast, if the worker would insert and screw in two screws simultaneously with each hand, the algorithm would determine that this is not possible according to the MTM rules and correct the resulting analysis.

6.5. Resulting MTM-UAS® analysis

The result of these four steps is a valid MTM-UAS® analysis that matches the interface data supplied by the VR tool. Table 6 shows the result for the example workplace. The analysis describes the assembly of the first two screws for the described work process. The result is a total standard time of 275 TMU (approx. 10 seconds).

To compare the results, an experienced MTM practitioner conducted a manual analysis using the video and the relevant object data as well as estimated distances. In this test case, the automatically generated analysis from the VR input data and the manual analysis were identical.

Description	Code	Q x F	TMU
Screwdriver into workspace	HA2	1 x 1	45
Place screw	AE2	1 x 1	55
Place screwdriver	PC1	1 x 1	30
Process time screwdriver	PTTMU	1 x 30	30
Place screw	AE2	1 x 1	55
Place screwdriver	PC1	1 x 1	30
Process time screwdriver	PTTMU	1 x 30	30
Sum	-	-	**275**

Table 6: Automatically generated MTM-UAS® analysis

7. Translation into MTM-HWD® analyses

The MTMmotion® interface and algorithms can be used to translate the motion data into various MTM analyses that have different application areas. While MTM-UAS® is classically used in batch productions, MTM systems like MTM-HWD® should be used for productions that have shorter cycle times (e. g. mass production) (MTM-1 2019; MTM-UAS 2019).

DOI: https://doi.org/10.30844/wgab_2023_3

Using MTMmotion® to get valid MTM-HWD® analyses follows the same process steps as for MTM-UAS®. That means technology providers like LIVINGSOLIDS can use the interface in the same way.

Additionally, the translation algorithm also follows the same procedure (see chapter 0). The first two steps are identical to those of MTM-UAS®. That means the data is validated and checked in the same way. Steps three (see chapter 7.1) and four (see chapter 7.2) are adapted to MTM-HWD® to realize the system process building blocks and system specific rules.

7.1. Translation into basic actions

In contrast to MTM-UAS® the MTM-HWD® algorithm almost never combines the various motions into basic operations. It rather translates them into basic actions for the creation of a valid MTM-HWD® analysis (view Table 7). Obtaining the screw and placing it on the screwdriver (Table 7, row 4-6) are translated into the basic actions "Obtain" and "Deposit".

<table>
<tr><th>object ID</th><th>side</th><th>arm motion</th><th>Basic Action</th><th>GraspMotion</th><th>CaseOfDeposit</th></tr>
<tr><td>2</td><td>right</td><td>ObtainObject</td><td>Obtain</td><td>Grasp</td><td>-</td></tr>
<tr><td>2</td><td>right</td><td>MoveObjectTo OtherPosition</td><td>Deposit</td><td>-</td><td>approximately B</td></tr>
<tr><td>2</td><td>right</td><td>HoldObject</td><td>no translation</td><td>-</td><td>-</td></tr>
<tr><td>1</td><td>left</td><td>ObtainObject</td><td>Obtain</td><td>Separate</td><td>-</td></tr>
<tr><td>1</td><td>left</td><td>MoveObjectTo PointOfUse</td><td rowspan="2">Deposit</td><td rowspan="2">-</td><td rowspan="2">close</td></tr>
<tr><td>1</td><td>left</td><td>UseObject</td></tr>
<tr><td>2</td><td>right</td><td>MoveObjectTo PointOfUse</td><td>Deposit</td><td>-</td><td>loose</td></tr>
<tr><td>2</td><td>right</td><td>UseObject</td><td>Hold</td><td>-</td><td>-</td></tr>
</table>

Table 7: translation of arm motions into interim result with basic actions

Since MTM-HWD® is a more detailed process building block system than MTM-UAS®, more influencing factors are processed in the algorithm. Most of them (e.g.: *TypeOfGrasp*) are read from the interface data and translated directly. Only a few are used subsequently to determine specific MTM-HWD® influencing factors, such as *GraspMotion* or *CaseOfDeposit*.

GraspMotion for example is the equivalent to *CaseOfGet* in the MTM-UAS® algorithm. It describes the way the hand or fingers gain control over an object before further moving it. *GraspMotion* is calculated using the object data as well as the values *TypeOfGrasp* and *Supply* which were provided for the arm motion.

7.2. Combination of different body parts

The rules to combine different body parts in MTM-HWD® are like those that are used for MTM-UAS®. As explained in chapter 6.4, the algorithm compares each Channel with motions with all other motion channels and checks if they influence one another. For example, the MTM rule for the remaining effective distance for an arm motion after a body motion is displayed in Figure 8.

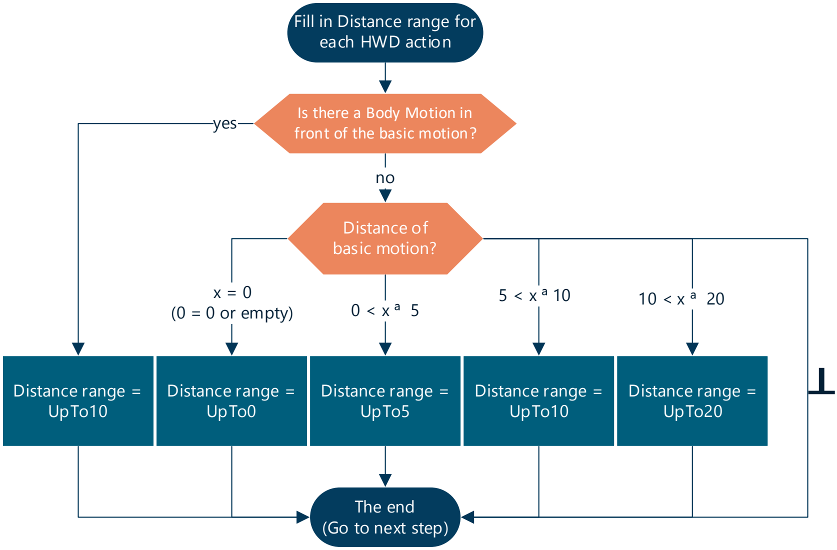


Figure 8: Determination of distance range by considering body motions

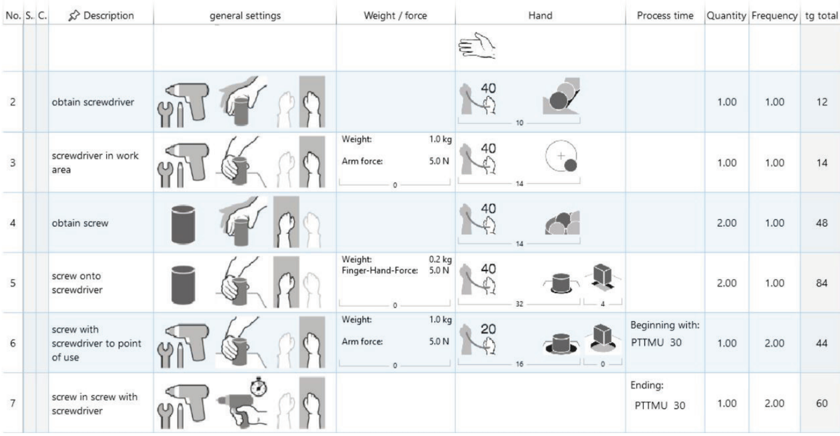
To determine the actual distance for an MTM-HWD® action, the algorithm checks every basic motion (origin in Channel 2 or 3) for the occurrence of a body motion (Channel 1) right in front of it. If this case occurs, the distance range for the MTM-HWD® action is set to UpTo10 (equals up to 10 cm). Otherwise, the distance of the basic motion is used to determine the distance range for every MTM-HWD® action as shown in Figure 8.

7.3. Resulting MTM-HWD® analysis

All these steps lead to an MTM-HWD® analysis that is consistent with the MTM-UAS® analysis. The screwdriver is taken into the work area, the first screw is placed onto the screwdriver and then screwed in with the screwdriver. This last part is repeated for the second screw. This process can be seen in the MTM-HWD® analysis in Figure 9 in column "Description". In addition, the analysis can be understood by looking at the pictograms. For example, the column "general settings" describes the object, what kind of HWD action is performed and which hand is

DOI: https://doi.org/10.30844/wgab_2023_3

handling the object. The second row refers to the screwdriver that is obtained with the right hand. Furthermore, the weight of the object and additional forces are shown for the MTM-HWD® analysis.



No.	S.	C.	Description	general settings	Weight / force	Hand	Process time	Quantity	Frequency	tg total
2			obtain screwdriver					1.00	1.00	12
3			screwdriver in work area		Weight: 1.0 kg Arm force: 5.0 N			1.00	1.00	14
4			obtain screw					2.00	1.00	48
5			screw onto screwdriver		Weight: 0.2 kg Finger-Hand-Force: 5.0 N			2.00	1.00	84
6			screw with screwdriver to point of use		Weight: 1.0 kg Arm force: 5.0 N		Beginning with: PTTMU 30	1.00	2.00	44
7			screw in screw with screwdriver				Ending: PTTMU 30	1.00	2.00	60

Figure 9: MTM-HWD® analysis

The influencing factors for the hand are listed in column "Hand". Row 5 shows the place motion of the screw onto the screwdriver. This process covers a distance range of 40 cm with a close fit of the screw while orienting it before placing it onto the screwdriver. The process time of the screwdriver can be viewed in row 6, column "Process time".

Other important values are "Quantity" and "Frequency". Due to the repetition of placing a second screw onto the screwdriver and screwing it in, the quantity in row 4 and 5 is set to 2 and the frequency in row 6 and 7 is also set to 2. There are additional influencing factors (e.g., upper body, trunk, or arm postures) that are not included in Figure 9, because explaining all of them is beyond the scope of this publication.

The result of this MTM-HWD® analysis has a total standard time of 262 TMU (approx. 9.5 seconds).

8. Conclusion and Outlook

8.1. Critical Discussion

For the first test cases using VR technologies, the presented approach has shown good results. However, there are some aspects that need to be discussed critically.

1. Completeness of VR data:

   Since the process relies on the transferred data from the VR tool into the data interface, two aspects must be considered. Firstly, it is necessary that the VR tool can model the necessary data in a VR simulation. Secondly, it is important that the data is input correctly by the VR user. A good example for this is the object data. If the simulation does not include object types or weights, the data cannot be translated, or the standard values provided by the algorithm are translated, which might not be correct for all cases.

2. Quality of the motion capture algorithm in the VR tool:

   To derive the correct process building blocks, the motions must be recorded properly by the VR tool. In the shown example case, all relevant motions were captured. However, the quality in a wide use must be checked in future cases.

3. Translation of motion data "as provided":

   The approach only focuses on the work process that was modelled in the VR tool. That means that exactly this motion data is translated without checking if it would make sense for the real product in a real production. If the process is modelled incorrectly or unnecessarily complicated, the resulting MTM analysis describes exactly that process. Therefore, it will still be necessary to involve an industrial engineer to check the modelled process and the translated MTM analysis.

When those aspects are properly handled, the approach can help industrial engineers to plan workplaces in a modern and efficient way. If VR technologies are already used in their company, they will need little effort to also get valid MTM analyses. It will be easier for them to model different variants and simultaneously get valid process descriptions and analyses, which helps choosing the best variants or to identify optimizations.

The interface was developed to be accessible for all technologies that record or generate motion data. As different technologies yield different data types as well as qualities while recording or generating motion data, the quality of the resulting MTM analyses might differ as well. However, the developed approach was designed to yield analyses matching the input data and thus, the success of the approach is not impacted by the quality of the input technology.

DOI: https://doi.org/10.30844/wgab_2023_3

8.2. Outlook

To improve the approach and thus its usability, several development steps will be carried out. Firstly, the number of industrial use cases will be expanded to test the approach with several additional workplaces. Secondly, other VR tools will be enabled to supply the interface data. Thirdly, other MTM process building block systems such as MTM-1® will be implemented. These steps aim to advance the combined use of VR and MTM in industrial companies.

Because the interface data was built so that it can be accessed by any technology that records or generates motion data, it is possible to transfer the approach to technologies such as human simulation tools like the ema Work designer (imk 2023) or motion capture suits like the Xsens suit (Movella 2023). The transfer of this approach would also offer starting points to develop interfaces that transfer motion data combined with process data from one technology to another.

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DOI: https://doi.org/10.30844/wgab_2023_3

Fostering Circularity: Building a Local Community to Implement Circular Processes

An Approach to Overcome the Barriers to a Sustainable Future

Jonah Schulz, Simon Hillnhagen, Matthias Schmidt

1. Introduction

To realise a globally sustainable future, the transformation of industry is an essential intermediate step, as currently, a large part of the greenhouse gases that cause demonstrable climate change are emitted by companies (Alvarez-Risco et al. 2022). Therefore, sustainable business models are needed, which can create value efficiently in the long term while minimising resource requirements and environmental impact (Ritzén/Sandström 2017). The requirements for such a business model are complex, as resource consumption is rising due to increasing population numbers and occurring price and availability fluctuations that strain supply chains (Geng et al. 2014). Considering in this context the fact that there is only a limited amount of resources globally available (Tu et al. 2019), it becomes clear that the resource efficiency of companies must be increased (Jesus/Mendonça 2018).

In this context, the circular economy approach is an essential building block to enable this development (Corona et al. 2019). This approach is therefore being discussed intensively in business and science, as it represents a concept specifically for companies to address the problems already displayed in a targeted manner. (Ritzén/Sandström 2017). The main goal of the circular economy is to minimise or, if possible, eliminate waste production and the need for newly mined materials by increasing resource efficiency. The latter would then lead to a stage of ultimate circularity (Potting et al. 2017). However, the global economy is still far from this state. The Circularity Gap Report (Circle Economy 2022) found that the global economy was only 8.6% circular in 2020. The conclusion is that over 90% of economic processes produce waste, require new raw materials for production processes and thus follow the classic linear business model.

Many governments and organisations want to counteract the current linear business models using the circular economy concept. Governmental proponents include, for example, countries such as China (Lieder/Rashid 2016), which has even legally committed to implementing a circular economy, and the entire European Union (European Parliament 2015). In addition, specific initiatives such as the

DOI: https://doi.org/10.30844/wgab_2023_4

"Circular Economy Roadmap" in Germany, the "Transition from Linear to Circular Economy" in India, and the "Circular Taiwan Network" are also pushing for greater use and implementation of a circular economy (Alvarez-Risco et al. 2022). The circular economy concept is also receiving increasing attention in the academic context. This can be seen in that renowned universities such as University College London or the University of Cambridge have set up special departments to deal with this topic. In addition, an increasing number of academic initiatives by universities such as the University of Oxford, the University of Harvard and the Massachusetts Institute of Technology emerged (Alvarez-Risco et al. 2022). The increasing focus on the circular economy is reinforced by the fact that the mass of research papers on the circular economy has increased sharply since 2017 (Ayati et al. 2022).

In addition to the strong interest from governments and non-governmental organisations, companies are also increasingly interested in moving towards the circular economy. Public proponents include, for example, companies such as Google, Amazon, Apple, Johnson & Johnson and Procter & Gamble (Alvarez-Risco et al. 2022). They all want to benefit from the positive effects of this business model, which have already been proven in numerous use cases (Liu/Bai 2014). One example of such a use case is the city of Kalundborg in Denmark, which has established a complete symbiosis of different companies to increase resource efficiency and reduce the burden on the environment as much as possible. This concept has proven its worth over the last 50 years (Kalundborg Symbiosis 2023). But circular business models have also proven their efficiency in other areas by achieving cost savings of 40 to 60% (Ellen MacArthur Foundation 2013).

However, despite the high level of interest from various parties and the positive practical results, the concept is predominantly unknown among the general public. A study from 2019 showed that for 75% of the interviewed people from the industry, the idea of a circular economy was unknown (Duurzaam Ondernemen 2019). The fact that there is not yet a consolidated model for implementing a circular economy (Ritzén/Sandström 2017) justifies that the concept itself is not yet sufficiently understood to realise a greater circularity of the overall economy (Jesus/Mendonça 2018).

In addition to the lack of understanding and the insufficient dissemination of the concept (Ritzén/Sandström 2017), there are other barriers to the implementation of a circular business model. These include, for example, the resulting complexity caused by the necessary holistic view of business processes. This means that in circular business models, all components of the value-adding process, from the choice of materials to product design and production, must be considered. Even the processes outside the direct value-creating process, such as data management and the selection of distribution strategy, must not be neglected (Ritzén/Sandström 2017). In addition to the enormous planning and implementation effort, this radical change in corporate processes also involves an indispensable socio-cultural change within the company, which increases the complexity of the change-over (Potting et al. 2017).

Currently, the transformation process represents an implementation risk for many companies due to the significant investment in terms of time and money. With the need for more understanding of the circular economy concept, the transformation process has a deterrent character (Rizos et al. 2015). In addition, only a few comprehensive examples in practice can provide a detailed determination of the expected financial benefits or generally answer whether a profitable implementation of a circular business model is possible for all companies (Ritzén/Sandström 2017).

The latter is directly related to the technical barriers to circular business models, as many processes require new technologies to implement circular processes. Suitable technologies, especially in recycling areas, are still insufficiently developed in many primarily specialised areas, thus limiting companies in their transformation opportunities. This point is a key barrier to the broad shift from a linear to a circular economy (Jesus/Mendonça 2018).

Beyond that, there are further barriers which, apart from the technological and financial aspects, also target areas of corporate culture, legislation and the customer. These barriers have been studied by different authors and are mostly congruent (Araujo Galvão et al. 2018; Kok et al. 2013; Ritzén/Sandström 2017; Shi et al. 2008). Accordingly, no clear driver or barrier hinders the large-scale implementation of circular business models. Instead, it is an overlap of different challenges that makes the transformation of companies more complex and thus slows it down (Jesus/Mendonça 2018).

Building on this, Leuphana University Lüneburg has set itself the goal of meeting these challenges in practice and supporting companies in their transformation. In the project "Transformation durch Innovation und Kooperation in Communities" (Transformation through Innovation and Cooperation in Communities), a network of different actors who can and want to implement a circular economy in the Lüneburg region will be established over the next five years. To this end, industry, politics, science and society partners must be integrated to enable mutual support and the associated exchange. In addition to implementing a circular economy with the resulting positive effects on the economic, ecological and social sustainability (Ayati et al. 2022) of the region, the project should also serve as a pilot project.

In addition to direct, practical and economic participation, the project intends to contribute scientifically to relevant research areas. This is made possible by testing new findings within the network to eliminate delays between knowledge generation and application in the best possible way.

DOI: https://doi.org/10.30844/wgab_2023_4

This contribution is structured as follows to present the planned approach in a detailed and orderly manner. In the following second part, the concept of the circular economy is defined and presented in more detail to obtain a clear picture of the object of investigation for the following chapters. Subsequently, in the third part, the individually planned phases of the project are disclosed, and the intention of each step is described. Based on this, the fourth part focuses more on the scientific contribution and the intended knowledge gain. In this context, some research fields are presented with considerable contribution potential. Finally, concluding remarks and a summary will precisely present the core of the overall project.

2. Definition of Circular Economy

Even though the topic of circular economy has attracted increasing attention in recent years, the idea of circular processes has been around for several decades. The first scientific articles on this topic were published as early as the late 1960s (Gregson et al. 2015), and since then, it has not yet been possible to come up with a widely accepted definition (Ritzén/Sandström 2017). For this reason, Kirchherr et al. (2017) compared a total of 114 different alternatives of the circular economy and derived the following definition:

> Circular Economy can be defined *"as an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers"* (Kirchherr et al. 2017, p. 229).

Similar starting points can be found in the definition of the Ellen MacArthur Foundation (2013). However, it refers more to the material side of sustainability than to the triple-bottom-line approach, which relates sustainability to ecological, economic and social development (Elkington 1998). Nevertheless, the Ellen MacArthur Foundation clearly illustrates how material cycles can be closed. These different forms are displayed in the so-called butterfly diagram.

This figure illustrates the possible processes for the cycle of finite and recyclable biological materials and shows that the material cycles can be closed at different points. It also addresses the separation of biological and finite materials, which was already presented by Michael Braungart in his Cradle to Cradle concept (Braungart et al. 2016). This separation shows that long-term planning must already be carried out in the early stages of product and process planning in order to be able to use the comprehensive strategies sensibly and comprehensively. On this basis, the figure shows that the cycles to be aimed for differ between biological and finite materials. While biological materials should primarily be returned to the environment after they have reached the lowest cascade, finite materials and products should always be kept at their highest value level and therefore also be returned to different points in the supply chain. This is represented in the diagram by the processes recycle, remanufacture and reuse for finite materials.

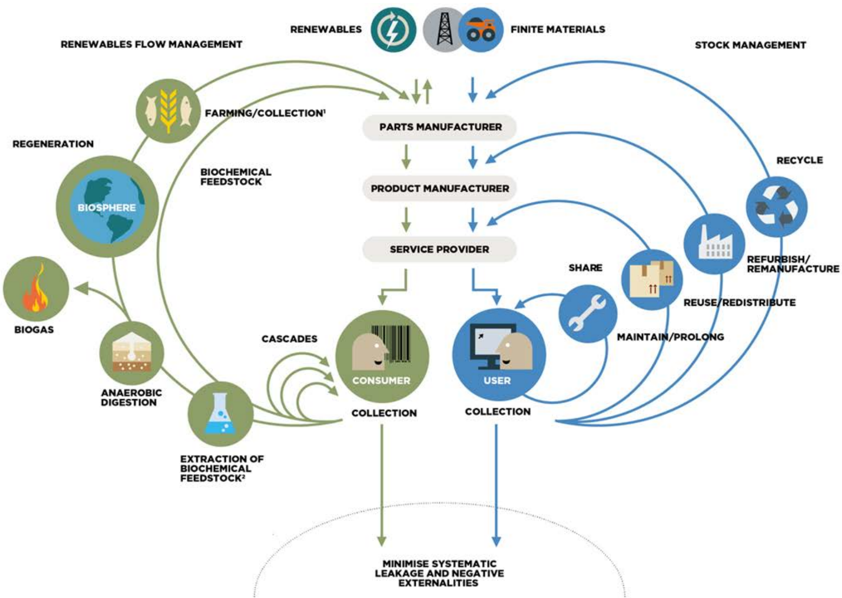

Figure 1: The Butterfly Diagram (based on Ellen MacArthur Foundation 2013, p. 24, 2019)

Potting et al. (2017) use a similar starting point. The authors identified different approaches with varying degrees of influence on the circularity of a system (Alvarez-Risco et al. 2022). Based on this, the "R-strategies" were ordered to generate a ranking of each approach. The result of this ranking is displayed in figure 2.

DOI: https://doi.org/10.30844/wgab_2023_4

This figure clarifies that there are various strategies for closing material cycles and making corporate processes more circular.

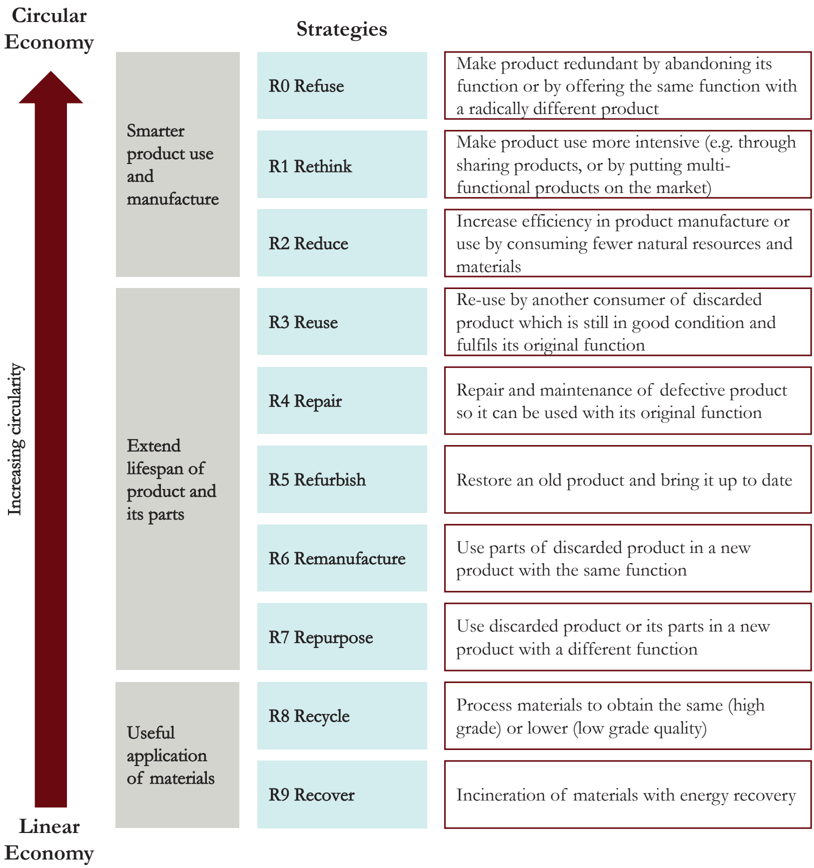

Figure 2: R9 model (based on Potting et al. 2017, p. 15)

However, the depth to which each of these individual strategies can be implemented and presented (Reike et al. 2022) increases the scope that must be considered in a holistic view of the circular economy concept. In addition, these strategies can be applied not only within a company's sector (closed loop) but also across sectors (open loop) (Farooque et al. 2019).

The considerable volume of different strategies and approaches has led to a gap between theory and practice, as practical relevance is often lacking (Ayati et al. 2022). This fact has already been uncovered by different authors and resulted in a call for the practice-oriented implementation of the approaches to be able to generate further sound knowledge (Angelis et al. 2018; Araujo Galvão et al. 2018; Ayati et al. 2022; Fehrer/Wieland 2021). This call is now being answered through the practical implementation of the planned project. The following chapter explains how the intended structure helps to unite theory and practice.

3. Structure of the Project

To establish a suitable basis for the upcoming project, elementary components in the literature were examined, which are needed to build a community and promote the Circular Economy's further development. Therefore, the structure of the project is divided into four different phases, which build on each other at the start of the project. During the project duration, these can influence each other and be processed agilely. The four phases are as follows:

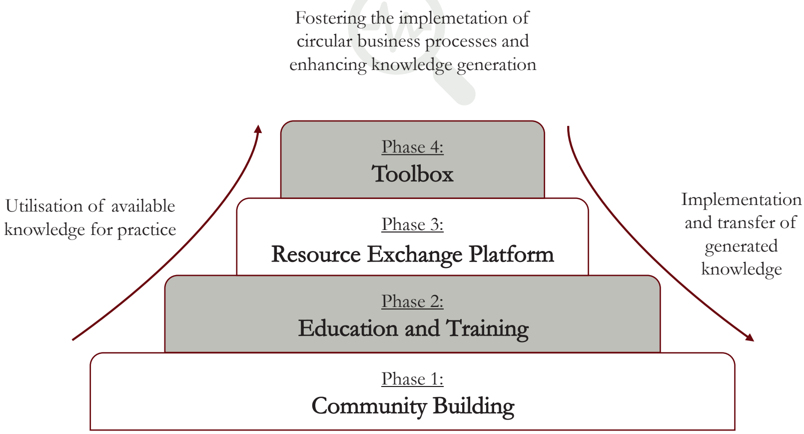

Figure 3: Conceptual Structure of the Project

The project's first part aims to build a community of different actors and interested parties to enable a mutual exchange. Based on this, the second step is to provide up-to-date and relevant knowledge to prepare all actors for further actions. These include, among others, the development of an online platform in the project's third phase, enabling and facilitating the exchange of resources in the sense of a circular economy. The procedures and processes used in this phase are to be continuously examined to finally, in the last phase of the project, allow companies to select the right strategies for them from various procedures in a targeted and analytical manner.

DOI: https://doi.org/10.30844/wgab_2023_4

All the steps mentioned pursue the overarching goal of first using existing knowledge and implementing it in practice. This implementation should ultimately be the catalyst for the ongoing generation of further knowledge regarding the Circular Economy. This generated knowledge can and should be used in the project to further develop the individual project phases. In this way, it can be ensured that a broad transfer of the generated knowledge takes place in the community that has been built up. In this way, the conceptual structure of the project ensures that, in addition to the new knowledge provided, direct value is also created for the members of the community.

How the individual phases are to be structured in detail will now be taken up in the following subchapters to create a sharper overall picture. The order of the subchapters follows the chronological sequence of the phases within the project.

3.1. Phase 1: Community Building

The aim of the community-building step is to enable communication between different actors in a supply chain. This is essential for closing material loops (Leising et al. 2018; Ritzén/Sandström 2017). For this, academic and public institutions are involved in creating an impetus for common frameworks, which also aim to ensure long-term support (Su et al. 2013). This linkage of different involved parties is a crucial step for the forcing of sustainable economic development. This is because the challenges related to holistic sustainability are too multifaceted to be solved comprehensively by one company alone (Gallo et al. 2018; Rossignoli/Lionzo 2018).

In this phase of the project, the community will initially serve the sole purpose of building relationships between the different actors, assessing readiness for the implementation of circular business models, and identifying problems and challenges already encountered in practice, as well as activities. The exchange will take the form of in-person meetings, such as topic-based meetups and discussion groups, workshops designed to promote understanding among the actors, and conferences, which will aim to advance the overall project.

To also achieve a higher frequency of communication and a faster reaction time to emerging problems, an online forum is also to be set up. Here, news about the current progress and results should be permanently visible, and questions from all project partners can be asked. The long-term goal is that the support will come from other project partners who have already gained practical experience in the respective area or who can provide support in a direct form. In the short term, however, Leuphana University will take on a moderator role in this context until the project partners' theoretical knowledge and practical experience are sufficient to help each other.

The latter pursues the goal of consolidating a deep bond and symbiotic relationship between different companies in the long term, moving away from a purely competitive approach. This should lead to a change in the company's thinking, which should develop from a company-centric focus to a holistic view of the system (Wiek et al. 2011). This is because exclusively profit-oriented value creation is not suitable to efficiently address the complex challenges of sustainability and social inequality (Montabon et al. 2016). It is important to emphasise that while circular business models are not focused on profit maximisation, economic growth is imperative for a company's sustainable development, and thus this is also an essential and central component (Bocken et al. 2016). In this context, economic growth is achieved through the cooperation of companies (Gallo et al. 2018; Rossignoli/Lionzo 2018) and through the maximisation of resource and energy efficiency (Bocken et al. 2016), which entails the growth of an economic system.

This collective thinking should be strengthened between different industry partners, as described above, but also between companies and political and academic partners. For example, through exchange with political partners, a consensus could emerge that leads to legislation that minimises the implementation risk of circular business models and promotes efforts on the part of companies (Ayati et al. 2022). This could also create incentives for other companies to deal with circular business models and to join the community that has been established.

Compared to the political partners, it is envisaged that the academic partners in the community, in addition to providing theoretical knowledge, can also directly influence the companies' further development. Possible approaches in this regard include the Living Lab method (Canzler et al. 2017; Claude et al. 2017; Compagnucci et al. 2021), which is intended to enable new scientific results to be tested and validated directly in practice. This accelerates knowledge generation and minimises implementation risk for companies through ongoing support. The projects successfully created in Living Labs can be continued by the companies and transferred to other business areas or products. In addition to the practical contribution, the results can be scientifically processed and thus immediately contribute to the overall project's progress. After processing, this information is made available at the conferences and in the online forum so that all project participants can participate and benefit.

The newly acquired knowledge will be taken up in the second phase of the project "Education and Training", in addition to the theoretical frameworks and models on the circular economy, to generate a direct practical reference.

3.2. Phase 2: Education and Training

The second phase of the project aims to establish knowledge and awareness of the circular economy and circular business models. For this purpose, workshops and courses can teach topics such as the R9 model (Potting et al. 2017) or approaches

DOI: https://doi.org/10.30844/wgab_2023_4

such as those of the Ellen MacArthur Foundation (2019). This step will lead to a reduction of the barriers to the implementation of a circular economy through company-enriched knowledge (Ritzén/Sandström 2017).

In addition to in-person workshops, teaching materials will also be made available on an online platform. These teaching materials will be in written and video graphics, enabling effective and efficient self-study. Making some materials available globally is conceivable to incentivise external parties to join the community and contribute to the overall project.

The main focus of this phase should be on providing teaching materials and a practical learning environment in the form of a learning factory. This can build on existing concepts of Leuphana University (Rokoss et al. 2021), which can then be continuously supplemented with different approaches and strategies of the circular economy. For example, the existing assembly-focused concept could be complemented with a material recycling process that entices participants to think about the far-reaching possibilities of the R9 model and implement it in a learning factory environment. Using this model can sharpen understanding and stimulate creativity among participants. As a starting point, versatile requirement profiles for the learning factory can be created using different scenarios using different strategies from the R9 model in defined cases. Here, the learning success of the participants can be favourably applied to their own company processes utilising knowledge transfer.

Building on this transfer, individual mentoring programs can be established on the part of Leuphana University. Once the knowledge and awareness of the participants have been created and the initial idea of how the circular approach can be incorporated into a specific company has been developed, an individual implementation plan can be generated in close collaboration in such programs. Such a plan can also be understood as generating knowledge, which can also be provided to other project partners and serve as inspiration. In some instances, the knowledge gained can also be extensively incorporated into the materials provided and the workshops to increase practical relevance continuously.

Once the initial implementation plans have been drawn up and circular business models are present in the target region, the third phase of the overall project can be initiated. This includes the further development of the already active knowledge online platform, which is primarily intended to facilitate the exchange of material between different parties. How this is envisaged is presented in the following subchapter.

3.3. Phase 3: Resource Exchange Platform

After sufficient knowledge has been anchored in the companies and the first circular processes have been implemented, the next phase is to create an opportunity to minimise the hurdles for exchanging materials between companies. In addition to the communication and exchange function, the online platform should operate as an online marketplace. Companies should be able to offer and make available by-products or waste from their production to other companies.

In addition to the pure offer, the products can be quantified according to quantity and quality to facilitate the buyer company's decision. By measuring the quantity and frequency of supply, long-term business relationships can also be established between companies, influencing production planning and control (PPC) through regular purchases.

By handling single transactions and regular material exchanges through the online platform itself, valuable data can be collected that can be used to develop the platform and its performance further. For example, using artificial intelligence and machine learning, the data can be used to develop matching algorithms that make it easier for companies to find suitable materials and make this process as efficient as possible. This could also bring together companies that would not have come together without this support.

The achieved connection of a wide variety of companies through material flows is pursued with a long-term goal in addition to the circularity achieved in the short term. If stronger material-related relationships are possible between certain companies due to the characteristics of their respective productions, this can be a starting point for deeper cooperation. For example, production processes could be adapted to make better or more extensive use of the by-products. Thus, this form of social interaction could close material cycles more extensively (Bocken et al. 2016) and, therefore, the overall system of different companies gains circularity.

Especially this strong interconnectedness and the emergence of a system consisting of different companies means that, compared to linear business models, new and unfamiliar processes have to be implemented for the company. This challenge will be addressed in phase four of the overall project by providing a toolbox.

3.4. Phase 4: Toolbox for Local Industry

The diversity of the different companies means that different forms of the circular economy and, thus, different processes will be practised in the companies. These processes will influence various objectives within the company differently, whereby the interdependencies still need to be clarified (Ayati et al. 2022). To counteract this barrier, the processes tested in practice are to be scientifically examined and analysed for interdependencies with specific objectives. The reviewed procedures will be summarised in a toolbox and made available to the companies.

This toolbox will help companies to choose from the available processes and to adapt the configuration of the different methods and strategies to the respective business model. This strategic decision helps support the company's sustainable

DOI: https://doi.org/10.30844/wgab_2023_4

development in the long term. Based on this, uniform guidelines and "best practices" can be isolated for different types of companies, further lowering the barriers to using circular strategies and increasing the speed of their implementation.

Since the toolbox creation is the last phase of the overall project, the exact orientation and characteristics will depend heavily on the previous results achieved. Based on this, the examination of the procedures will focus not only on the implementation path but also on the effects on the corporate objectives that have emerged as central in the course of the project. These can include, for example, objectives from the area of logistics performance and costs (Schmidt/Nyhuis 2021), but primarily objectives that are relevant for measuring circularity.

The latter is an important field of research that is to be further explored by the overall project, among others. In this context, the fourth phase and the research results are thus interrelated. In addition to the measurement of circularity, there are other research fields to which the project can contribute. Which research fields these are will be highlighted in the following.

4. Scientific Contribution

In addition to the practical benefit generated by the direct support of the companies, a scientific contribution should also be generated from the academic side through the in-depth practical research of the circular economy. This follows the call of various authors (Angelis et al. 2018; Araujo Galvão et al. 2018; Fehrer/Wieland 2021). Due to the scope of the overall project and the complexity of the circular economy, different research fields have arisen.

These are shown in the following figure, taking into account the macro-, meso- and micro-levels of the circular economy, which are taken up in the definition by Kirchherr et al. (2017).

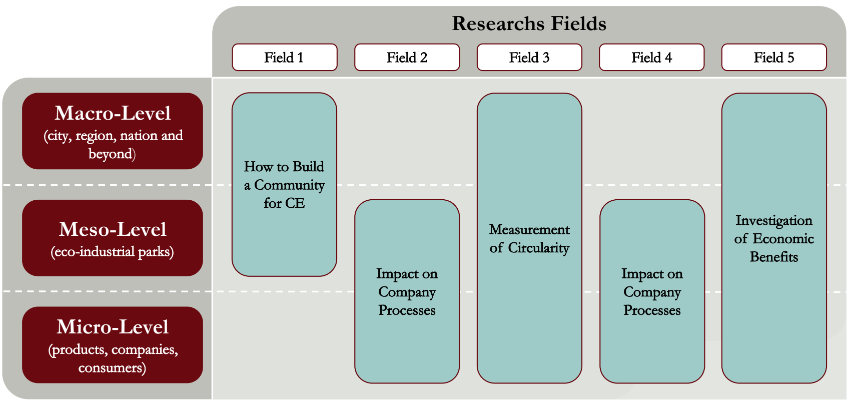

Figure 4: Presentation of the Research Fields Considered and their Impact Level

The size of the respective fields does not indicate the scope or the importance of the individual research field, but only the influence or the affiliation to the respective macro-, meso- and micro-Level. It is impossible to place the research fields under consideration on just one level (see Figure 3). For example, the first research field cannot be clearly assigned since community building can refer to entire regions and the symbiotic association of a few companies. Similarly, in the second research field, it cannot be said that business processes only refer to one company or one product because the influence on the external supply chain design still needs to be determined. In comparison, the measurement of circularity can be relatively clearly assigned to all three levels. This is because circularity can be determined at the most minor (product) level and scaled to an entire nation. The fourth research field can be located in the same way as the second since the influence of a new business model indisputably directly Impacts a company (micro-level) and can thus also shape a system of different companies (meso-level). Furthermore, only a minimal influence on the macro level will be possible as long as it is not a disruptive innovation. However, this will be neglected in this context. As the last research field considered, the investigation of economic benefits again refers to all levels since, for example, both a product line per se (micro-level) and the economic performance of an entirely circular economy (macro-level) can be investigated. Thus, here too, there is a wide range of possible results. The following sub-chapters discuss how the respective content contributes to the research fields mentioned.

4.1. How to Build a Community for CE

The very approach of building a community can already generate new insights. This refers to the lack of experience in building a community that focuses on the circular economy. Due to this lack of experience, there is a large gap between theory and practice (Ayati et al. 2022).

Through the practical establishment of such a community and the detailed documentation of this process, conclusions can be drawn about the overall project's success. Through recurrent evaluations and interviews with project partners, efficient and practical working steps and procedures can be identified and developed. In the same stage, it is possible to analyse procedures that negatively influence the project to improve or discard them for subsequent work steps within the project, if necessary.

This way, developing a practicable process model can help future organisations build such a community. Such a process model would result in lower implementation hurdles, a predictable output, and justifiable time predictability. Such a development would have a strong positive influence on future projects on the topic of the circular economy.

DOI: https://doi.org/10.30844/wgab_2023_4

4.2. Impact on Company Processes

In addition to the results for future projects to build communities, direct conclusions can be drawn for companies and their processes. The extent of this scope and the associated value of these results is already clear from the definition by Kirchherr et al. (2017), which divides the circular economy project into the micro, meso and macro levels. To be successful in the circular economy, a transformation must be made on all three levels (Kirchherr et al. 2017), and how this transition can be shaped is of great value to companies.

For example, at the micro level, which refers to individual products or companies, a circular economy's impact on a company's PPC could be examined. Expanding existing framework models, such as the Hanoverian Supply Chain Model, is conceivable to provide companies with a practicable application model (Schmidt/Nyhuis 2021). The challenge here is that different process configurations are possible due to the available strategies for implementing a circular economy (Potting et al. 2017; Reike et al. 2022). This increases the complexity and versatility of the processes to be investigated. However, this point, in particular, underlines the importance of this project to sustainably support companies in configuring their internal processes and the corresponding planning and control processes.

If the view is directed from the company's internal to external processes, the focus shifts to the influences on the meso-level. At this level, circular supply chain management (CSCM) offers an exciting approach, as it combines the idea of the circular economy with the conventional methods of supply chain management (SCM) (Farooque et al. 2019). This topic and, thus, this field of research is of utmost importance, as sustainable business models and supply chain design are interdependent and must be considered together (Lüdeke-Freund et al. 2017). Concerning the research project, the question of how the configurations of supply chains will or must change to move from a linear to a circular economy could be explored. Possible research topics regarding the configuration of supply chains include, for example, order fulfilment principles (e.g. make to order, make to stock, assemble to order, engineer to order), process design (supplier and customer connectivity in circular processes) and methods and procedures for cross-company coordination of capacities and inventories in the circular economy. To enable this transformation, ways can be explored how this design can be done (Angelis et al. 2018) and which specific measures lead to a sustainable and resilient supply chain (Negri et al. 2021).

To implement the points mentioned above on a broad scale, small and medium-sized enterprises must also be involved in the transformation and are supported by guidelines and incentives (Panigrahi et al. 2019). At this point, an extension of the research field already described arises, which detaches itself from the entrepreneurial focus and links up with the first-mentioned research field. In this context, it is primarily in the public interest to support companies to implement the transformation broadly at the macro level as best as possible. In this context, investigating which form of support is needed by different companies can also be a research topic. This would allow measures for policy to be derived.

4.3. Measurement of Circularity

Another important field of research is the measurement of circularity. The broad interest in this field of research can be explained by the fact that the circularity of a product or an individual company can be measured, as well as the circularity of an economic system, a region or an entire nation. All these different expressions of circularity are of central importance for corporate and public objectives, which justifies the need for a transparent means of measurement.

Currently, many of the available performance indicators are criticised for addressing only a few aspects of circularity (Åkerman 2016; Geng et al. 2012; Pauliuk 2018; Saidani et al. 2017) and thus not providing an exact measure (Saidani et al. 2017). This is because challenges such as the great complexity of the processes to be studied and the difficulty of data collection make comprehensive measurement challenging (Corona et al. 2019). To make progress in this area, one of the research priorities is to develop one or more parameters that are both valid, reliable and practicable for companies (Bannigan/Watson 2009), taking into account all aspects in the sense of the triple-bottom-line (Kirchherr et al. 2017).

In this context, assessment tools can be continuously investigated and further developed. These tools evaluate different alternatives for action to decide which alternative makes the most significant contribution to general circularity. Possible examples are Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Input-Output Analysis. It is conceivable to develop a metric based on these tools that comprehensively consider all aspects of circularity (Corona et al. 2019).

4.4. Development of New Business Models

To provide companies, in particular, with even more extensive opportunities, new business models can also be developed based on the results of the studies on LCA. This can significantly contribute to the broad implementation of a circular economy (Bocken et al. 2018) and counteract the low implementation frequency of such models (Linder/Williander 2017; Stål/Corvellec 2018; Tukker 2015).

The complexity of this research field is extensive, as there are already various approaches in the literature on how circular business models can align themselves. These include efficient material-technical loops, effective product-service loops, social-collaborative loops and symbiotic ecosystems (Fehrer/Wieland 2021). On this basis, new types of circular business models can be developed, or specially

DOI: https://doi.org/10.30844/wgab_2023_4

tailored solutions can be created for project partners. Both could serve as inspiration for future research projects and thus make a significant contribution to progress towards a circular economic system.

4.5. Investigation of Economic Benefits

Besides contributing to sustainability, circular business models should be profitable, even if maximising profit cannot be the sole focus (Montabon et al. 2016). However, circular business models still need to be more fully proven economically to entice companies to adopt such business models. This can be achieved through extensive research on the various economic benefits, such as reducing material costs, increasing raw material availability, improving efficiency in implementing environmental regulations and growing profits. Companies will consider this path for themselves only when the circular economy concept has proven itself economically.

However, since a circular business model can work economically (Liu/Bai 2014) and help save costs (Ellen MacArthur Foundation 2013) is not enough, the transformation itself must also be included in the analysis. It is conceivable to examine the transformation of individual project partners in different cases and then compare the time and financial expenditure with the resulting benefits. In this way, the defined value of the transformation for a respective company is ultimately determined. This value will impact all components of the triple-bottom-line, even if the economic part will have the most significant influence on the final motivation.

This economic value has a substantial governmental interest in addition to the entrepreneurial one. Even though circular business models are an approach that does not refer to the profit maximisation of an individual company, it is necessary to investigate and quantify how the economic performance of a system behaves. If it turns out that economic performance is increased by the widespread implementation of circular business models, this will result in political interest for the accompanying transformation. This research and these results would thus significantly Impact both the economic and societal levels.

5. Summary and Outlook

This contribution presents the structure of the described project in conceptual form. The four defined project phases aim to give companies an impetus from research and politics and to support them in developing and implementing circular business models.

The first step is to build a community by facilitating communication between participating companies and other interested groups in politics and science. In addition to meetups and conferences, the core of this communication will be an online platform that will enable the exchange of information, knowledge and experience.

Based on this, after project partners have expressed interest and joined the community, a training programme will be initiated, which should enable the development of further practice-oriented knowledge that can be learned in learning factories, for example. The project partners with new skills can now develop and apply their circular business models, which a Resource Exchange Platform supports. Finally, the emerging processes within the partner companies will be continuously analysed to conclude interactions between individual processes and relevant objectives. These results will be made available to the project partners in a structured form.

In addition to directly shaping the local economic structure, the project results are to be academically processed to have a global influence on further economic development. In this contribution, the research fields of community building, the impact on business processes, the measurement of circularity, the development of new business models and the general investigation of economic benefits were named as examples. The potential for further development of these research fields is considerable due to the practical relevance of the project.

In the future, both the practical and the scientific project results should support the transformation to a sustainable (regional) economy to achieve a long-term economically attractive, ecologically efficient and socially sustainable future.

DOI: https://doi.org/10.30844/wgab_2023_4

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DOI: https://doi.org/10.30844/wgab_2023_4

Creative Intent and Reflective Practices for Reliable and Performative Human-AI Systems

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1. Introduction

"AI will probaly most likely lead to the end of the world, but in the meantime, there'll be great companies" (Sam Altman, OpenAI Co-Founder & CEO). Even though this statement supposed to be polemic and was later characterized as "partly in jest" (Shin 2023), it is the founder behind ChatGPT who signed the open letter on AI risks for humanity: "Mitigating the risk of extinction from AI should be a global priority alongside other societal-scale risks such as pandemics and nuclear war (https://www.safe.ai/statement-on-ai-risk#open-letter) – a declaration among leading CEOs of the US digital industry and researcher in computer science that was published in June 2023.

"The only things in my life that compatibly exists with this grand universe are the creative works of the human spirit" (Ansel Adams, Feb. 20, 1902 – Apr 22, 1984). The American environmentalist and landscape photographer Ansel Adams died exacly one year before Altman was born. Both are convinced that Big Sur, an area in California with lush vegetation, would be the best place to live on earth. Both reflect on the universe from their very different professions and let us think about human creative intent as the most valuable source of sustaining humanity in future (Dewey 1934). Nowadays it is supposed to be a mastery of sophisticated technology. As Maeda (2002, p. 39) argues we risk that technology becomes "an end in itself in society and industry" when design is not driven by human creative intent. Since ancient Greek creative intent is described as the way how human beings use and combine their contextual knowledge and experiences to find new solutions (Dewey 1934). Novelty of the outcome was not the most important characteristic in the origin writings, rather the underlying process of generating solutions while using all senses.

The world could recently observe that it was indigenous knowledge of how to survive in the jungle when four children between 13 years and 11 months managed to stay alive for 40 days in the Columbian rainforest after a plane crashed. If it is human creative intent augmented but not replaced or disturbed by technology there might be a way to cope with the risk of technology and to use it for better

DOI: https://doi.org/10.30844/wgab_2023_5

life and better working conditions (Fischer 2018) even in less developd and priviliged countries. The prerequisite is to put human creative intent and reflective practices in the center of technology design.

The movement of Industry 4.0 neglected the human-side of generating solutions while giving high attention to autonomous systems communicating with each other and regulating challenges by smart sensor technology (Lasi et al. 2014). The vision for manufacturing was that "products control their own manufacturing process" (Lasi et al. 2014, p. 239). With respect to digital services the idea was that technology takes the responsibility for regulating critical situations, e.g. for higher safety in autonomous driving (Fagnant/Kockelman 2015). In the first wave of Industry 4.0 there was a belief that sensor technology could work autonomously and provide the necessary sensory input of the system. Expectations related to this vision seemed to be too high; a revolution of autonomous systems did not take place. From a technical point of view the reason was attributed to underdeveloped connectivity and interoperability due to missing standards across firms and industries (Jepsen et al. 2020). But there is also the critical reflection that sensor technology is too limited to manage critical interfaces and to provide reliable and resilient solutions in unforseen situations. The human sense and contextualized knowledge for keeping systems work was missing in the technology design.

Meanwhile, there is a vision of Industry 5.0 aiming at higher human-centricity in terms of collaborative hybrid systems. This movement aims to keep the human in the loop by design and to elaborate on semi-autonomous instead of autonomous systems (Nahavandi 2019). Even though the expression semi-autonomy is considered as characteristics of robots it includes both sides, the autonomy of the human actor and the autonomy of the non-human actor which are interrelated on system level.

We want to elaborate on this human side and ask how it can serve as most valuable source of reliable systems. Our core argument is that human-centricity is a necessary condition to reach and sustain the intended outcomes of AI-based systems in terms of safety, quality, accuracy and reliability. The reflection on human creative intent and how to build semi-autonomous systems around is a matter of avoiding the risks for humanity expressed in the recent declaration of leading AI experts. The aim of this contribution is to explain why human creative intent as an input and throughput factor and reflective practices for a continuous interaction between AI and humans is a crucial point to sustain semi-autonomous systems and gain solutions on a relational basis – a circumstance demanding new methods in co-design and co-creation.

In the next sections we outline the relational constructs keeping systems work from a theoretical point of view. We will illustrate the meaning and relevance with the help of five use cases of high relevance for a bright future of our societies. The following discussion gives emphasis to design principles of how to keep human creative intent and performative interaction in the center of technology development. Finally we give an outlook on necessary research methodology for the future research agenda.

2. Relational constructs of human-AI systems

2.1. Creative intent as individual relational practice for system development

Nowadays intent is a construct of contemporary political psychology with emphasis on interest-driven outcomes that can be explained by contextual factors of the interest groups. Among these scholars there is stil a reference to the roots in ancient Greek phylosophy (Neblo 2007). We trace back to these roots as it allows us to integrate a broader discourse of relevance for systems in work and business instead of primarily considering a political agenda.

“Intent” is a concept coined by the ancient Greeks, later developed through the work of John Dewey (1934) and applied across industrial contexts by Rogala et al. (2020). The relevance of human creative underpinnings for technology development and especially the risks of their absense was outlined by Maeda (2002). The construct brings together human contextual and environmental factors with the processes of creating and making, and as such, has high relevance in today's complex systems design. Intent requires realisation through performative actions. It is a flexible, dynamic construct that can be described as key to driving developmental progress towards solutions. However, it is often far from a perfectly formed solution, it is neither irrelevant to finding one.

Intent, as a concept, is a key part of creativity (Maeda 2002): It is a quality that becomes modified in response to evolving solutions, it reflects specific, contextualised knowledge and it shapes the onwards flow of decision making and enquiry. In creative domains, intent forms a guiding marker for creativity. It is a synthesis of human analytical, emotional and relational processes. Creative intent is a driver for curiosity – the 'what if questions' and at the same time way to it’s answer. It describes creativity as a process and not as a novel outcome.

Referring to the system level and conceptualizing intent as a relational construct the contextualization plays a pivotal role. Rheinberger (1997) argues in correspondence with environmental biology, that the limitations of experimental process are a function of the application context. In his concept of “experimental system” Rheinberger (1997) describes a space where contextual considerations create networked thought, rather than a more abstracted and procedural test/experiment/evaluate workflow common to lab procedures. It is intent that helps steer a path towards outcomes – forming a guiding framework for contextualised experiment within a complex system.

DOI: https://doi.org/10.30844/wgab_2023_5

Among the German speaking research community there is a synonomous construct which is especially considered as relevant in demanding work settings: “Kompetenz” is defined as the ability to act and interact against the background of new tasks and demands and to find coping patterns and novel solutions within continuously changing process. The meaning of “Kompetenz” is somehow routed in the German vocational system (Erpenbeck 2002) and addresses the meta-ability for self-organization in unfamiliar situations that require to activate and combine cognitive, methodological and social abilities to solve problems as an issue of performative action (Erpenbeck 2002; Heyse/Erpenbeck 2007; Erpenbeck et al. 2017; Wilkens et al. 2006). E.g. the multi-level model proposed and validated by Wilkens/Sprafke (2019) builds on coping with complexity, self-reflection on action, combination and cooperation within and across organizations in order to develop situated solutions within a contextualized learning process on system level. "Kompetenz" requires a deep sense for classifying situations and needs, understanding technology, material and service not just on a cognitive level testified with certificates of qualification but also with all human senses and in a socialized manner (Erpenbeck 2002). This allows to not just operate according to task descriptions but to reflect on meaningful solutions (see figure 1, left hand side).

Elaborating on these synonomous constructs it becomes obvious that their relevance rises when there are systems with high dynamics without a pre-defined best way or solutions but rather depending on relibale performative interactions. This is the case for AI-based systems, especially when the technology gains agentic character and operates in an autonomous manner (see Kaartemo/Helkkula 2018 and next section).

2.2. Understanding the relational character of AI

"Artificial Intelligence (AI)" is nothing more than a terminology which has no parallels to individual intelligence. In its origin the ability of a software could also have been named as computational detection of patterns with the help of neural networks (Barthakur 2023; Wilkens 2020). There is no general definition for AI and the meaning evolves with new generations of technology (Launchbury 2017; Xu 2019). The current state of the art in technology development is artificial general intelligence in the meaning of “intelligent agents that will match human capabilities for understanding and learning any intellectual task that a human being can” (Fischer 2023, p. 1). The generative AI ChatGPT gives an example that goes into this direction (Barthakur 2023, see also section 2.4). Considering cases with AI use in the workplace it is more algorithms dedicated to solve specific and pre-defined problems where the technology was pre-trained for and fine tuned on the basis of a mass of data. This gives “machines the ability to reason and perform cognitive functions such as problem solving, object and word recognition, and decision-making” (Hashimoto et al. 2018, p. 70) in a specified field. These AI-based operations result from machine learning (ML) for detecting patterns in terms of supervised learning (detecting pre-labeled patterns, e.g. distinguishing between fault and correct products in production line), unsupervised learning (detecting relationships between data points, e.g. consumer preferences for a set of products) or reinforcement learning (algorithms aiming at a specific goal based on punishment and reward functions, e.g. gender equality in personnel selection) (Russell/Norving 2021). This goes beyond former processes of automation resulting from pre-programmed static commands as AI can learn from experiences and new data gathered from operational processes and thus act and develop autonomously (Haenlein/Kaplan 2019) without further human intervention (van Rijmenam/Logue 2020) as outlined in the origin Industry 4.0 senarios considering AI-based systems communicating with each other autonomously and regulating challenges by smart sensor technology (Lasi et al. 2014).

Considering this "autonomy" of the system from the perspective of learning and development it is important to note that the autonomy is not multi-directed. The underlying learning process is completely different from individual learning processes with their potential to learn and develop beyond and out-of-the-box while combining insights and experiences from different contexts (Wilkens 2020). Since an ML approach supports learning in only one direction, primarely on a single-loop basis of further optimizing the system but at the same times undermines double-loop learning options while doing so, Wilkens (2020) characterizes AI-based learning as a "double-edged sword". Autonomous AI systems cannot cope with unfamiliar situations they were not pre-trained and fine tuned for. This makes a difference to the creative intent of human beings. The relational space of AI technology for generating solutions is narrow and tends to follow a chain-like approach. This bears risks for unforseen situations and challenges demanding for contextualized new processes of generating solutions.

The movement towards human-centered AI (see Shneiderman 2022, 2020) aims at both, intelligent augmentation of human actors involved and a safty culture reflecting on the accountability at critical interfaces and reliable practices between the involved human and non-human entities. The vision is to "enhance human performance with systems that are reliable, safe, and trustworthy" (Fischer 2023, p. 1). These scholars claim the relational space that was often neglected when AI-based solutions became implemented but left critical interfaces without principles for reliable organizational practices (see Widder/Nafus 2023).

2.3. Relational practices as core of value creation – The service-dominant logic

It is exactly relational practices that is in the center of new business thinking and value creation. Under the lens of the service-dominant logic (SD logic, Vargo/Lusch 2004, 2008; Blaschke et al. 2019) scholars emphasize interaction, collaborative and co-creative practices as the core of relational value creation in business ecosystems (Vargo/Lusch 2016). There is a high potential for

DOI: https://doi.org/10.30844/wgab_2023_5

continuously interacting with customers, finding and further developing customer specific solutions for certain fields of established and new business (Coreynen et al. 2017). Even though the SD perspective has an almost twenty year record and was considered as crucial for manufacturing industries in Western economies (Zimmermann et al. 2021) the meaning of generating value from relational practices is not combined with specifications for the operational level in AI-based systems. Especially the crucial interfaces for generating solutions have been negelcted or underestimated (Thewes et al. 2022).

Paschen et al. (2021) analysed the human-AI-co-creation in sales marketing on empirical basis and describe that AI tools perform enabler and operator functions while human agents serve as experts, creators, conductors and reviewers. Galsgaard et al. (2022) make a conceptual outline for radiology and argue that a division of tasks and separation of expertise would be a constraint for technology implementation while a role concept of collective human-AI-expertise or sense of collective expertise would make systems work. Currently, there are scenarios for separated and integrated tasks or even role concepts in parallel but the meaning of relational practices on system level remains underexplored.

2.4. Facing the challenges of relational practices in semi-autonomous systems

In an ideal world there would be semi-autonomous systems allowing us to exploit the potential of AI while making use of human creative intent in order to benefit from system development with respect to single-loop and double-loop learning and thus enhance resilience (Evenseth et al. 2022). This would make systems robust and adaptable as they have a both-directional option for generating better solutions in terms of high quality, accuracy and safety (Shneiderman 2020; Widder/Nafus 2023). The prerequisite is that ML algorithms provide and sustain a space for human creative intent as valuable part of a co-created solution. Currently, semi-autonomous AI systems have limited agility in constructing experimental situations by which creative intent can be explored and unfolded. This can be illustrated by use fields of high relevance for society and a bright future.

Use case: semi-autonomous driving

The vision of autonomous driving is the most popular use field for reflecting (semi-)autonomous systems (e.g. Fischer 2018). It is an AI application with tremendous impact on societal level. The human side of the current discourse raises many questions including ethical issues if technology has to “decide” whether one persons' life goes over the other in face of unavoidable car accidents. Concepts for semi-autonomous assisted driving aim to keep the driver in the loop for critical situations. Thus, there might be a focus on human creative intent but the technical approach at the same time undermines it and raises certain questions as the outlines for the driver role are underdeveloped. How can a person who is not concentrated on driving and not trained by daily routines in driving a vehicle better regulate a critical situation spontaneously than the technology? What type of experience is necessary to perform this type of task? Is experience in non-assisted driving a prerequisite to manage these situations? But this would be only the case for the first generation of drivers adapting to semi-autonomous driving. Is the driving licence of the future rather a training in how autonomously driving systems work and how to interact with them in case of emergency – similar to the training for pilots. The questions show that the critical interfaces of (semi-)autonomous driving are not sufficiently reflected and that sophisticated human-AI-role concepts for making systems more reliable and safe are missing. Creative intent requires contextual knowledge and experience which is not considered in a meaningful manner as long as the system development follows the technological potential and treats the individual potential as residual factor. Dongol et al. (2020) highlight how interactions between environmental contextual information, autonomous systems, and regulation needs to be approached outside of existing models with contextually informed methods that go beyond hazard-focused and procedural compliance. The authors note however that challenges still remain with regard to finding appropriate test scenarios and that further work is necessary on the handover processes between AI and humans. In this space, reflective practices and particularly *reflection in action* – on the part of an autonomous system – may provide a theoretical context for re-assessing the human-AI interface. This would require another approach of technology development on the one hand side in experimental settings with the behavior of drivers in the center of analysis and a focus on reactions and reflections in order to find solutions for a corresponding supportive technology-based driver assistance. On the other hand ethnographic research observing the change of (driving) behavior and individual routines while being transported by a semi-autonomous vehicle needs to be analyzed in oder to understand new reflective practises instead of relying on former models of driving and drivers role that do not correspond with the new context factors.

Use case: manufacturing

Manufacturing is an advanced use field for integrating AI in production flows and work processes. The range goes from exoskeletons for physical health protection, eyeware for supporting operational tasks or digital assistance systems in production and supply chains in order to balance the mental and physical shape of an operating person but also for the overall condition monitoring at the critical interfaces (Romero et al 2016; Hinrichsen/Bendzioch 2019). The aim is to make systems more efficient and reliable for all stakeholders. This is complemented with training approaches for employees in how to handle and interact with the digital tool (e.g. Gorecky et al. 2014). Employees are considered as users and important actors of an implementation approach dedicated to the potential of the technology. The key challenge here is that the system design follows an engineering approach of standardising processes for production flows while considering the technology as a tool for regulating systems' need and compensating individual shortcomings

DOI: https://doi.org/10.30844/wgab_2023_5

in fatigue, disabilities etc. (Wilkens et al. 2021). The underlying process optimization reduces (unintendendly) the space for human creative intent for performative interaction for system regulation. It is not the individual who is considered to manage systems' weeknesses but the machine managing individual shortcomings. This can be acceptable for pre-planned chains following a good-dominant logic with standardizable transactions but can easily become a hazard for generating solutions in collaborative value creation networks.

Use case: Software development for industry applications

The software development of AI-tools to be applied in other user domains, e.g. manifacturing, healthcare or education, is decribed as a rather modularized process even within software companies depending on organizational internal checks and balances at critical interfaces of the development process including issues of data reliability and ethical guidelines that are brought to standards and checklists but however can easily be circumvented or at least not be treated in as deep sense as they are supposed to be. This is documented to be a challenge of organization and process chains in modularized development processes (Widder et al. 2021; Widder/Nafus 2023). In addition to this challenge, the domains are almost not involved in the development process. Data classification for software tool takes place without domain knowledge even though a contextualization is important for a meaningful use of data. This severe problem has especially been described for the heathcare sector (Thewes et al. 2002; Morrow et al. 2023). This raises questions with respect to the trustworthiness of AI applications as meaningful and reliable data classification needs the knowledge of user domains and not just of software developrs. This is almost not the case in daily practices. Tools dedicated to human-AI interaction miss human-human interaction in their process of development. The sense for interaction at critical interfaces is not a taken-for-granted routine in technology development. Interfaces are rather considered as a challenge of technological interoperability one aims to get rid of. As a consequense reflecting and designing the necessary space for creative intent and performative practices to make solutions better and reliable is not in the center of the process of software development. This is neither the case for organizational internal processes nor for processes between the developr and the user domain. The hidden ideal type stil tends to follow the vision of Industry 4.0 of autonomously interacting digital systems.

Use case: radiology

There are meanwhile visions for using AI for medical diagnoses in radiological images following an Industry 5.0 approach. Scholars describe radiologists as system regulators which make use of AI-applications in order to enhance the accuracy of their diagnoses and to better interact with other medical disciplines as an issue of system regulation (Dewey/Wilkens 2019). There is the idea of a collective expertise and related role development of radiologists (Galsgaard et al. 2022). The core idea is that AI supports the standard classification of images and provides a safety net for physicians who further validate their individual diagnosis and especially spend their time on critical cases. These concepts build on the creative intent of the professionals to which the technical system provides the space and therefore give a good example. Organizational process descriptions need to support this type of human-AI interaction. Currently, this is the struggeling point because concepts are projecting state-of-the-art interactions to the future and thus tend to neglect that standard operations have to be adapted when they are dedicated to high reliablity through human-AI system regulation and thus need to be build around human creative intent and its further development.

The first generation of radiologists working with AI-based image classification has a high profession and deep sense of interpreting images while making use of all human senses and contextual information. This allows them a continuous reflection on action and decision making while collaborating with AI. Future generations are trained on AI technology from the very beginning and thus need to develop an understanding when to trust and rely on the diagnosis proposed by AI and when to mis-trust it, how to develop the expertise to be able to mis-trust the technology as an important element of AI literacy and to be able to have the sense for another diagnosis. The space for creative intent has to be considered in role concepts. So far, it currently exists in the first user generation but tends to slowly disappear with future generations (similar to the future generations of drivers), especially if user domain knowledge is not sufficiently integrated in the software development process (see use case above). There is also a counterproductive side-effect from technology that has to be taken into consideration. AI speeds up the process of diagnosis - this is considered as an issue of enhancing productivity while integrationd AI – but this may unintentionally reduce the time for creative intent that cannot develop sufficiently in high speed settings as the load for individual reflection decreases with the amount of images to be reflected in a time unit. There are entire system dynamics that have to be taken into consideration in order to design hybrid systems based on human-AI-interaction in a manner that allows to reach the targets of high reliability in the long run.

Use case: Generative Pre-trained Transformer (GPT) applications in Higher Education

Natural Language Modeling is on the research agenda since 2010. Data scientists started to develop Large Language Foundation Models in 2017 and came up with the first public available Conversational Large Language Foundation Model in November, 30, 2022: Chat GPT III is the third generative pre-trained transformer (GPT) application offered to a broader group of users by OpenAI. The speed of global dissemination of the test version was higher than for any other technology before.

DOI: https://doi.org/10.30844/wgab_2023_5

Since then a generative AI-tool is in broad use in the societies all over the globe. The much more advanced and licenced professional version ChatGPT IV came out in March 2023. While ChatGPT III is based on 175 billion textual data, ChatGPT IV is based on 100 trillion textual data (Barthakur 2023).

A "time for class survey" from March 2023 (Student n=1,545, faculty n=1,692, admin n=205) (Bharadwaj et al. 2023) shows for the use field of higher education that in the first three months of the free version it was only 9% of faculty using the tool but 29% of students. Students prefere to use the tool for individual feedback and tutoring while writing assignments especially while brainstorming and structuring their essay but rather not for writing the whole text (Bharadwaj et al. 2023). All respondents of the survey are convinced that the tool improves individual learning strategies and learning outcomes. The licence price of the professional version is adapted to students' budget – at least in highly developd Western countries. Strategies for learning and generating solutions already changed among the future generation of global leaders and this is of impact for our future. The AI-based co-creation of learning processes and learning outcomes is on the daily agenda. What does this imply for keeping creative intent in the center of generating solutions? This is an open question demanding for further research. In the current state of development students tend to use and experiment carefully with a tool in order to generate better solutions. It seems to be part of the opacity that students show high consciousness for the possible but unknown weaknesses of the tool and thus intensify their reflective practises. This would be in line with the key targets of higher education, boostering the learning process towards human reflective practices (Barthakur et al. 2022). But this might change in future when students have higher trust in GPT outcomes and submit AI generated assignments which are in the next step evaluated by AI tools activated by faculty. In these constellations all involved parties have high proficiency in operating with AI-based digital tools to safe time for other tasks and interests but tend to loose creative intent in generating even better outcome in person. Keeping creative intent in the center of AI development is a challenge for the future of an intelligent humanity. The education system is the transformer for all other domains and thus needs to find solutions.

Providing systems with the capacity to continuously further develop and generate meaningful contextual interactions through hybrid human-technology reflective processes will be the core challenging issue for all institutional fields operating with AI.

3. Discussion

We outlined with the help of different use cases that the design of AI-based system solutions is often not dedicated to keep human creative intent continiously high. Even if there is an approach for the first adopters as decribes for healthcare and higher education, the design perspectives for future – not just on a technological basis, but also on an organizational basis – are not yet clear. In the use field of higher education there is the most explicit consciuousness for human reflective practices (Barthakur et al. 2022) but even this field is now challenged by generative AI applications with a high risk to act autonomously instead of interactive between individual learners and technology. There is a potential for humanity to steer into a bright future with semi-autonomous systems benefitting in their further development from individual learning and reflection and from machine learning mechanisms of data processing. But this is a narrow ridge that can easily reverse in an opposite direction. For the bright side system design principles and related organizational strategies are necessary, including technology development, organizational learning and individual learning & development. Corresponding methods have to complement each other in a consistent manner in order to enhance the reliability on system level. Coping with the risks of AI while exploiting the benefits is an issue of sociotechnical design and development.

Reflecting the state of the art descriptions of the use cases against the background of what it implies for keeping human creative intent in the loop is summarized in figure 1. Considering current design approaches in the light of individual competence development or space for reflective practices dedicated to creative intent leads to the conclusion:

(1) that is is especially the autonomy of systems that can disturb creative intent and negatively effects individual learning and development (see bottom of the figure),

(2) that most industry applications and taken-for-granted practices of buying and implementing AI-based solutions reduce the human side to rather uncritical users of AI tools with pure application skills (see middle of the figure) and

(3) that process outlines dedicated to high crerative intent are either missing or do only exist for early adapters or first generation users (top of the figure) while late adopters might only have application skills (see below).

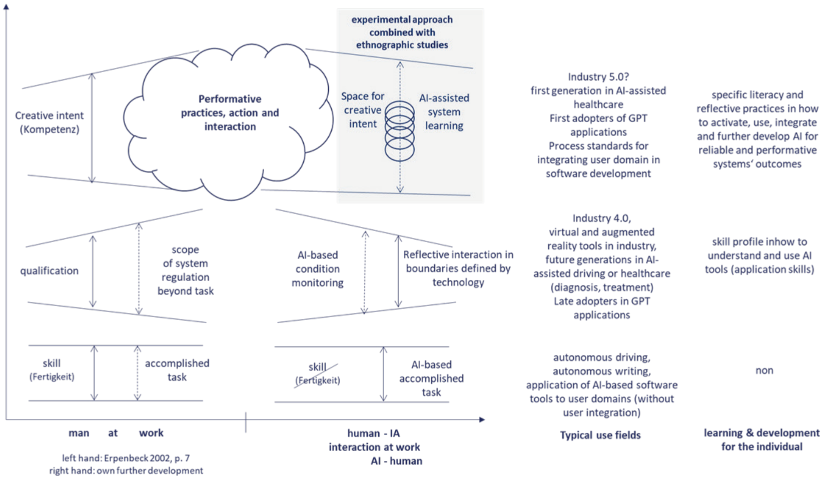

Figure 1: Design principles of human-AI interaction and their impact on performative practices through human creative intent

4. Outlook: An agenda for methodology development

Methodologies in AI development rather rely on optimization and outcome criteria instead of providing the necessary space and complementarity for benefitting from creative intent in order to reach higher targets in system level reliability. One of the key problems of modelling is that human creativity is not a fully generalisable system: there is no one flowchart of creativity, no singular set of processes. Instead, the interactions and networks that define creative responses to real-world situations occupy a layered, rhizomic configuration that resides between experience and experiment. This interplay needs to be addressed in future research approaches. The way in which this conceptual space of creative development operates shares much in common with organisational models such as SD logic. Yet, industrially, creative thought is often assumed to be part of a linear, goods-based logic – resulting in outcomes, design features, or traditional "creative" destinations such as branding, artwork or media applications. All of these situations represent product-based thought. Creativity itself is not an assembly line, or a set of prescribed processes. That doesn't mean that it functions without structures or relationships, and it is these which underpin decision making. SD logic and AI systems based on current machine learning or conversational large language models consisting of neural networks share similar architectures: it is not possible to find the "value" expressed directly in the structure of the network itself, it is created through the relational interaction of the component parts.

It is surprising therefore that SD logic-based workflows and AI systems which require contextual interaction are not generally associated in systems design processes. However, both methods depend on the similar relational information generation, on emergence and on pragmatic validity, to substantiate their activity.

Starting the other way round it is important to note that intent is subject to emergence. Creativity – as an idea – encompasses consideration of emergent behaviours and as such, has become polarised between views of creativity as straight forwards inspiration and views of creativity as fully-worked-through craft processes. In reality, neither is likely to be the sole driver for outcomes. Bringing creativity together with Rheinberger's (1997) ideas for experimental systems results in a consideration of ideas which are either directly expressed through design or those which arise through emergence. Current AI systems have difficulty in situating emergence, as it is of itself not a product of a technical rationality.

Established methods in co-design such as design thinking need to be revisited under the conditions of generative AI as development cyles remain to sequent like and to interconnected. Future research methods have to consider systems with meaningful contextual interactions with hybrid human-AI reflective processes. Crucial to forming a contemporary description of intent that is relevant for workplace semi-autonomous system design is the idea of reflective practice established by Schön (1983). Reflective practice is not an adjunct to professionalism, it is an integral part of being a professional practitioner. Reflective practices have been adapted and applied to high risk work environments and professional training scenarios in high reliability organizations with high responsibility in health and safety (Jordan, 2010). As Schön (1983) argues: this is of particular importance in areas with high situational awareness and mindeful enactment of routines where complex systems, creativity and professional practice interact. For Schön (1983), there are two key types of reflection: reflection as an activity in the abstract, and reflection in action. It is proposed here that reflection in action is critical to understanding the interaction between context and intent, and therefore, a critical process for underpinning semi-autonomous system design. Reflection in action has much in common with experimentation, in an artistic sense, rather than one inherited from the sciences with its clinical character of simulations. This is the concept where we propose to elaborate on in future research especially combined with ethnographic studies that are considered as most important for organizational settings with human-AI-interaction systems (Anthony et al. 2023; Widder/Nafus 2023). This allows to become part of an interactive community, e.g. of learners continiously using GPT applications and to observe how their way of asking questions, design solutions, trust and mis-trust a system develops over a longer time period.

"Experiment" in science is considered as a method with rigorous, perhaps linear, process of thought to deduct specific information about a specific problem, for example in trying to what the boundaries of tolerance are on an engineering design.

DOI: https://doi.org/10.30844/wgab_2023_5

By its very nature, the act of experimenting in a scientific context may be involved with working with a closed system: with deliberately limited use-cases, input conditions and a controlled environment. This is meaningful for testing tools (see bottom and middle of figure 1) but it is not a suitable approach for exploring the organic development of systems based on generative AI. Exploring the necessary space for creative intent requires to understand where are the roots of personal styles, new forms of interaction and related reflective practices with unexpected outcomes. This is the opposite to a science-based process validation. The core research question is how the relationships between human experience and experimental practice with AI-based applications emerge to form contextual knowledge that is essential to cope with unforseeable situations and high risks. The aim is to explore where are the critical spaces in which creative intent occurs and further develops, which situations and unstandardized context characteristics are necessary what is the time that needs to be reserved in technical supported systems for sustaining creative intent. Otherwise the augmentation potential of AI cannot be exploited. "Experimental designs" coping with these needs are living lab approaches that make contextualization to a design principle. This is why they are closely connected to ethnographic studies, e.g. in outlines of participatory studies on platforms. As far as the parameters for reflective practices have been explored an interacting and complementing technical system can be further developed. The challenge for future work is not to build AI after the human brain. The crucial question is how to develop AI that supports and sustains the creative intent that makes the difference in quality of life and quality of work in terms of safety, reliability and trust? Research facilities such as the research building ZESS for the engineering of smart product-service-systems provide such a research environment with living lab character (https://forschung.ruhr-uni-bochum.de/de/forschungszentrum-fuer-das-engineering-smarter-produkt-service-systeme-zess). And there are international counterparts, e.g. the institute and facilities for safe autonomy at the University of York, UK (https://www.york.ac.uk/safe-autonomy/facilities/). We invite to collaborate with us in the outlined inquiry for which engineering expertise is essential.

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Smart, Sustainable and Socially Valuable: How Digital Textile Microfactories can Contribute to a Brighter Future

Pouria Arfaiee, Marcus Winkler, Meike Tilebein

1. Introduction

The traditional textile and clothing industry (TCI) is undergoing a significant and rapid transformation (Bebchuk et al. 2017, Berg 2022). This transformation is driven by factors such as volatility, velocity, variety, complexity, and dynamism (Boyle 2022, Brown 2022), necessitating the adoption of digital solutions (Wascinski et al. 2018). Here, digital networking across the entire value chain offers speed, individualization, efficiency, sustainability and high quality, with a strong potential for innovation and consumer interaction (Kiel et al. 2017, Winands et al. 2022). By establishing flexible production systems focusing on decentralized manufacturing as well as on-demand products, the TCI can shape new concepts that contribute to customer value, sustainability and even add to social entrepreneurship.

In order to promote such flexible production systems, Microfactories have recently been subject to research and development (Montes et al. 2019) which offer new possibilities for the TCI in the form of a Digital Textile Microfactory (DTMF). A DTMF is an end-to-end digitally networked development and production process for textile and clothing products (Winkler et al. 2022). Its digital backbone allows for speed, efficiency, high quality, and deep consumer interaction leading to a great innovation potential in a wide area of applications and business models. (Winkler et al. 2022)

Such DTMFs include a number of new technologies, such as digital textile printing or 3D knitting as an additive manufacturing technology. Digital Textile Microfactories thus show a new technological approach to clothing production, from a customer's body scan to the 3D simulation of the individual garment to digital printing and cutting or 3D knitting to the finished product (Artschwager et al. 2022). Using this smart approach, better sustainability could be achieved compared to traditional textile production.

DOI: https://doi.org/10.30844/wgab_2023_6

The aim of this paper is to systematically explore in which ways Digital Textile Microfactories can contribute to a brighter future by looking at their digital technologies and analysing their potential contribution to sustainability and social value. Section 2 reviews the basic concepts of DTMFs. Section 3 aims to explore in general the potential benefits of Digital Textile Microfactories, in terms of sustainability aspects and their impact on adding to social value. Section 4 will provide a comprehensive presentation of the recent digitally-driven technologies in the TCI used for DTMFs, with a special focus on digital textile printing and 3D knitting and elaborate on the specific sustainability potential of these two case studies. Finally, Section 5 focuses on discussing the findings, summarizing how DTMFs can contribute to a brighter future as a smart networked, sustainable and socially valuable way of textile production, and pointing to further research needed in order to detail and quantify the general potential described in this paper.

2. Basic Concepts of DTMFs

DTMFs have been in existence in various forms and characteristics for several years as a technical implementation. The first Microfactories were described in Japan in the 1990s (Mishima et al. 2002), and since then, the evolution of this manufacturing concept has resulted in a commercially feasible alternative to traditional manufacturing. The aim of this section is to introduce basic concepts of a DTMF which include its application settings and technologies.

2.1. Development of DTMFs

The textile and clothing industry has a long history of offshoring since the 1960s (Kunz et al. 2016), resulting in the development of intricate supply chains (Kunz et al. 2016). Despite the widely recognized advantage of low labor costs in developing countries (Bolisani/Scarso 1996, Kunz et al. 2016), there has been a notable shift towards reshoring in the industry starting in the 2010s. The motivations for reshoring are diverse and include factors such as the need for enhanced flexibility, greater control over the entire production process, commitment to environment protection, the closeness to customers and skilled labor, and more (Pal et al. 2018, Moore et al. 2018).

In the past years, the COVID-19 pandemic was another important issue which had a significant impact on different industries including the TCI. This unprecedent pandemic has caused disruptions in global value chains and complicated the transportation of intermediate products, resulting in significant losses for many multinational companies and a subsequent decline in global GDP (Kersan-Škabić 2022). This has further accelerated preexisting issues in the supply chain such as shortening of the value chain, refocusing on regional trade links instead of global value chains and reshoring activities (Kersan-Škabić 2022), bringing priorities such as digitalization to the fore (Zhao/Kim 2021).

Europe has a strong tradition of research and development, particularly in advanced manufacturing technologies (European Comission 2020). By bringing textile production closer to European centers of innovation, companies can benefit from the latest advancements, such as DTMFs which practice automation, digitalization, and sustainable manufacturing.

At present, DTMFs are used for three types of products: knitted fabrics, home textiles, and clothing made from textile surfaces (Winkler et al. 2022). They cover the entire development and production chain from customer to finished product, utilizing digitalization to optimize the complete process.

In contrast to traditional textile production workflows, which involve manual, labor-intensive steps from design to garment sewing (Lushan 2018), the DTMF is a model of the future that allows for competitive production of individualized products, with the potential for regional and on-demand production through the use of digitally networked and automated processes. This seamless digital networking of production steps enables optimal material and energy consumption, faster processing times for orders, and high flexibility to quickly respond to market needs.

Moreover, the implementation of DTMFs can potentially address challenges such as counterfeiting and socio-ecological concerns through digitaliization in product development and local production.

2.2. Technologies

The emergence of DTMFs is a response to the digitalization of value chains in Industry 4.0 or Textile 4.0. DTMFs use digital technologies to create value across various stages of the textile and apparel industry. The aim is to cater to individual customer demands, small quantity requirements, and savings in product development by integrating various value-adding stages.

Simulating the garments together with the customer for virtual fitting generally offers significant advantages. DTMFs' new technology approach even goes one step further in this context. It links the 3D simulation of apparel directly with production. The solution enables a complete, digital process chain from the initial body scanning, through 3D simulation and design, to digital printing/cutting or 3D flat knitting up to the final product. Technological solutions for simulation, textile design and marker-making, digital printing, single-layer cutting, automated knitting pattern generation and 3D flat knitting are integrated. Figure 1 shows two possible workflows of production lines in DTMFs.

DOI: https://doi.org/10.30844/wgab_2023_6

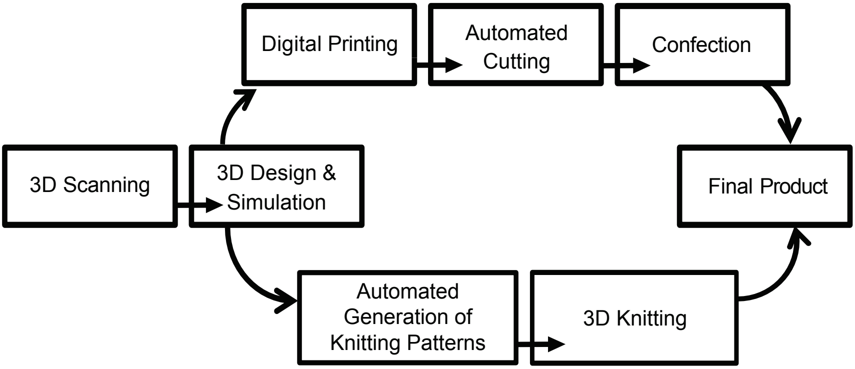

Figure 1: Digital Textile Printing and Knitting:
Two possible workflows of production lines in DTMFs

2.3. Business Models and Settings

Business models for DTMFs can utilize the benefits related to the new technologies. Hence, typically DTMFs can be used to address individual customer needs, to produce and reproduce small series fast, or to make sampling and prototyping more efficient (see also Section 3.2. for details).

DTMFs can be configured in different ways to support various application areas. Apart from being used in a "Fab Lab/ Technology Centre" setting for open purpose use, there are different settings for a commercial use of a DTMF. The first setting is the "Factory-in-Shop," which is located in a retail or selling environment that prioritizes customer interaction and has a fast turnaround time for production. The second setting is the "Standalone Factory", which has the capacity to scale up production and offers fast and flexible on-demand production, such as high-speed printing using multiple printers. The third setting is the "Factory-in-Factory," which is a dedicated workplace in a textile or garment factory for specific production jobs, such as sampling or producing lot-size one items (Winkler et al. 2022). Finally, the fourth setting is the "Virtual Factory", in which assets could be geographically as well as organizationally widespread due to their digital connectivity and communication.

The utilization of the first three settings enable the integration of a DTMF as a unified process, encompassing all production steps in a centralized location. On the contrary, the fourth setting allows for the production of digitally networked samples across various countries, utilizing specific elements of the integrated DTMF concept (Artschwager et al. 2022).

3. DTMF's Potential Contribution to Sustainability and Social Value

The TCI is faced with ecological, economic and social challenges of sustainability and is recently pushed to develop customer-oriented and sustainable value chains. Wherever sustainability aspects are significant, DTMFs provide good arguments in all three dimensions of sustainability because of their digital backbone (Tilebein 2019b).

The objective of this section is to show in general the potential of DTMFs to change the textile value chains in a sustainable way. In addition, different forms of positive impacts that a DTMF could make in local society are considered in this section justifying its capability of adding to social value.

3.1. Ecological Dimension of Sustainability

With respect to ecological and environmental aspects, the DTMF contributes to the current trend of ecological sustainability in production. The reduction of carbon footprint, waste, and material resources are central goals in this context.

Implementation of a DTMF process causes reduction of transport and logistics, compared to conventional processes, along the value chain, thereby decreasing the carbon footprint (Tilebein 2019a). The DTMF has a significant impact on reshoring, which involves relocating production closer to where products are purchased. By bringing production closer to the customer, the distance products need to travel is reduced, resulting in lower transportation distances, logistics costs, and environmental impact.

Moreover, in the case of larger series production, virtual engineering used in a DTMF plays a crucial role in minimizing transportation and production costs, particularly during the collection development phase. Through virtual engineering, designers can collaborate remotely, eliminating the need for physical transportation of prototypes and samples. This not only reduces costs but also reduces the carbon emissions associated with transporting materials and products. Additionally, even in cases where DTMFs act as partners in geographically widespread business ecosystems, the use of virtual communication and data sharing can significantly minimize transportation needs (Tilebein 2019a). By leveraging digital technologies, DTMFs can stay virtual for as long as possible, sending data files instead of physical products. This approach reduces the reliance on physical transportation, further lowering carbon emissions and environmental impact.

DTMFs offer significant opportunities for reducing overproduction and waste, promoting a more sustainable production process. Several key factors contribute to waste reduction in DTMFs:

DOI: https://doi.org/10.30844/wgab_2023_6

- Prototypes and simulations: DTMFs utilize simulation technologies to create prototypes on-site, replacing the need for numerous physical prototypes (Tilebein 2019a). This reduces the number of physical models required and contributes to waste reduction.
- Enhanced supply chain efficiency: Digital technologies employed in DTMFs enhance supply chain efficiency, minimizing instances of wrong deliveries and damaged goods. This optimization reduces resource consumption and mitigates waste generation.
- On-demand production: DTMFs minimize overproduction and the generation of excess inventory by producing goods on-demand leading to a significant reduction in waste generation.
- Implementation of virtual fitting and shopping advice: DTMFs can integrate virtual fitting and shopping advice, often powered by artificial intelligence (Tilebein 2019a). These tools empower customers to make informed purchasing decisions, thereby reducing the need for product returns and eliminating associated waste generation.
- Individualized made-to-measure products: DTMFs demonstrate potential in the production of individualized made-to-measure products, particularly in fashion and health textiles. This customization approach meets customers' expectations and lowers the number of product returns and respective waste generation resulting from issues such as poor fit or insufficient functionality (Tilebein 2019a).

Overall, DTMFs play a pivotal role in carbon footprint, material and waste reduction by minimizing transportation needs and overproduction, optimizing resource utilization, implementing virtual technologies, and producing tailored products on-demand. These practices contribute to a higher efficiency in material resource and energy use, thus enhancing ecological sustainability of textile products. For a more detailed assessment and quantification of digitalization's contribution to sustainability in a DTMF, there should be a model-based evaluation method with all sustainability indicators considered (Weiß et al. 2023).

3.2. Economical Dimension of Sustainability

From an economic perspective, the DTMF process facilitates manufacturing costs evaluation and poses more efficient value creation, flexibility, and customization of products and services. This automation, digitalization, and increased connectivity throughout manufacturing value chains leads to reduced lead times and costs (through efficient use of capital, resources and space), and enhanced quality.

Additionally, new sustainability-driven business models based on novel value creating mechanisms can achieve increasing customer satisfaction. The DTMF can be applied to various business models within both Business-to-Business and Business-to-Customer contexts to address challenges and drive profitability (Winkler et al. 2022). The foremost application is in response to customer demands for personalized products of high quality. This can be effectively achieved through the implementation of fast local value chains and organizational structures that capitalize on end-to-end digitalization, opening up new opportunities. Apart from small lot sizes, which is particularly relevant for product individualization, there are other promising applications and business models related to sampling, reordering, event-driven production, and locally centered manufacturing. These applications also benefit from the utilization of digitally networked end-to-end design and production processes (Winkler et al. 2022).

The consistent use of CAD and simulation makes entirely new designs possible here that were previously reserved for haute couture. This also makes the rapid, resource-saving production of small series and one-off items a realistic possibility (Tilebein 2019b). Furthermore, by increasing data availability and transparency in intra- and inter-firm logistics, lead and storage times can be reduced. As a result, logistics costs can be reduced significantly due to the end-to-end digitalization.

Although promising, DTMF-based business models could as well face archetypical challenges with regard to upscaling and growth. Among these challenges, the limits to success archetype could apply. In particular, different capacity restrictions and growth dynamics of process steps involved in the respective DTMF can affect perceived customer value and related purchasing behaviour (Martinez Jaramillo/Tilebein 2023).

Yet the economic advantages of DTMFs have sparked a noticeable trend among several fashion retailers towards adopting in-house manufacturing, often through the implementation of the Factory-in-Factory setting. This strategic decision enables retailers to exert greater control over their supply chain, while also reaping the benefits of accelerated speed to market and enhanced sustainability practices (McKeegan 2021).

In summary, DTMFs can contribute to economic sustainability by reducing manufacturing and logistic costs, enhancing value creation, and adoption of new sustainable business models.

3.3. Social Dimension of Sustainability

DTMFs offer improvements in the social dimension of sustainability, in addition to their ecological and economic characteristics. Customization applications play a key role in enhancing the social aspects of DTMFs. By offering personalized designs, colors, labeling, and made-to-measure products, DTMFs can meet individual demands and increase customer satisfaction.

DOI: https://doi.org/10.30844/wgab_2023_6

The proximity of DTMFs to the consumer market provides several social benefits such as shorter delivery times, resulting in customer convenience. Moreover, this proximity allows DTMFs to have better control over labor relations, promoting social justice in the production of ready-made clothing.

DTMFs actively involve customers, motivating them to contribute to improving social sustainability. This engagement fosters consumer empowerment and a sense of responsibility.

Data transparency is another significant advantage of DTMFs that contributes to social sustainability. It enables DTMFs to focus on innovation and socially responsible production activities. By having access to transparent data, DTMFs can develop new channels and approaches that strengthen customer relationships, ultimately leading to competitive advantages.

Furthermore, DTMFs have the potential to expand into educational and hobby fields. This expansion opens doors for new users and cultivates the creative potential of the younger generation, which often faces limited opportunities for self-expression. Additionally, DTMFs contribute to training individuals who will assume manufacturing responsibilities in the future, ensuring a skilled workforce for the next generation.

In general, DTMFs improve social sustainability through customer satisfaction and engagement, data transparency as well as expansion into educational/workforce-training fields.

3.4. Social Value

Social value can be created by changes driven through Social Innovations (SI), which have gained a great attention in recent times (Eichler/Schwarz 2019). SI can be described as changing social relations, involving new ways of doing, organising, framing and knowing (Haxeltine et al. 2016). On European level SIs are granted the same importance as traditional innovations (Sabato et al. 2017). Thus, SIs are regarded as a solution for most of the challenging problems facing today's society and for mitigating inequalities inherent to traditional solutions (Cruz et al. 2017, Angelini et al. 2016).

Especially in a technology-driven environment, like DTMF, there is a high potential for SI, by offering new possibilities in developing individualised products in small lots or for niches. This covers new methods of working, new business models, new spaces of knowledge generation using DTMFs as design labs (creating emotional intangible values), making labs (transforming skilled labour into material value to increase the common good) and place labs (creating spatial, community and social values) and may lead to some extent to a transformation of the industry which is realized through a community supported by a digital platform.

4. Two Case Studies of DTMFs

This section aims to concretize the concept of DTMF by focusing on two key technologies: digital textile printing and 3D flat knitting, and the related DTMF workflows as outlined in Figure 1. Exploring the sustainability and social value contributions of these core technologies, will shed light on the practical implementation of DTMF and its potential to revolutionize the textile industry towards a more sustainable and socially conscious future.

4.1. DTMF with Printing

4.1.1. Process Description and Technologies

Factors such as dynamic market trends, evolving consumer preferences, customization requirements, sustainability concerns, reshoring initiatives, and technology-driven business models have propelled the adoption of digital printing (Artschwager et al. 2022). Conventional printing methods consume significant energy, water, and valuable resources. In contrast, the DTMF presents a sustainable manufacturing solution that incorporates digital textile printing, minimizing resource consumption and environmental impact (Artschwager et al. 2022). Table 1 highlights the main characteristics of analogue and digital printing through a comparison (Artschwager et al. 2022).

Analogue Printing	Digital Printing
Less flexible	Flexible and versatile
Expensive	Low inventory and risks
High pollution	Sustainable, lower water consumption
Simple repeating patterns	3D effects (high creativity)
Limited colors, gradation and details	Unlimited colors and gradation
Hard to personalize	High potential of personalization

Table 1: Comparison between analogue and digital printing

The development and implementation of DTMFs has enormous potential to trigger a fundamental change in processes within the TCI. This is also supported by developments in digital printing. Textile printing is one of the DTMF's core value creation steps, as it is very environmentally friendly, adaptable and can be integrated into digital design software (Artschwager et al. 2022). For ensuring a con-

DOI: https://doi.org/10.30844/wgab_2023_6

tinuous digitally integrated workflow, the processes of the DTMF should be completed by digitalized communication between all value creation steps during the manufacturing. For this purpose, in the following, a full workflow of a production line in a DTMF that takes the digital textile printing as a core process will be explained:

3D scanning:

Technology for 3D body scanning can be used to create digital twins and virtual try-ons in a 3D simulation program. This can be applied in made-to-measure production and used to obtain body data on demand, which can then be integrated into existing processes. The scanner can replace traditional tape measurements with digital measurements on a personalized avatar. This enables the reuse and comparison of measurement data in the long term (Shen 2020).

3D design and simulation:

The design process begins with creating designs in CAD software that involve mapping digital versions of garments with realistic materials such as colors and textures onto virtual models. These avatars can be created using body scanning technology as described above to adapt and grade cuts to individual measurements (Artschwager et al. 2022). This realistic representation allows for the visualization of the interaction between the material, cut, and body, which can help in virtual fit analyses (Lin/Wang 2014), thereby reducing the number of physical samples needed and saving costs. After finalizing the design, a 3D simulation is used to prepare it for cutting out followed by Raster Image Processing (RIP) which is used for creation of a "print and cut" file (Artschwager et al. 2022). This file consists of multiple layers displaying various elements, such as contours and textures, and includes QR codes and position markers for accurate positioning during production (Artschwager et al. 2022).

Digital textile printing:

In the subsequent step, the fabrics are printed with unique designs using the digital printing process, which is the core process (Moltenbrey/Fischer 2021). In this specific DTMF process the necessary production files are directly generated from the 3D simulation environment. The RIP program mentioned earlier makes it possible to prepare the design data with accurate colors.

Automated cutting:

The DTMF uses QR codes and position markers to accurately identify the position of each component and the material during the cutting-out process. This enables fully automatic cutting of the material with the help of a camera (Artschwager et al. 2022).

Confection:

The final step in the DTMF process is to join the individual components together to produce the final product, which can be done using various methods such as sewing or ultrasonic welding machines (Artschwager et al. 2022).

Figure 2 summarizes the workflow of a production line in a DTMF, with digital textile printing as a core process (Artschwager et al. 2022).

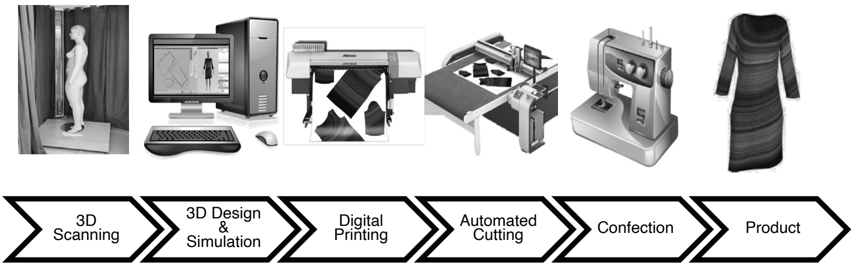

Figure 2: Workflow of a production line in DTMF, with digital textile printing as a core process

4.1.2. Contribution to Sustainability and Social Value

Digital textile printing makes significant contributions to ecological, economic, and social sustainability. In terms of ecological sustainability, digital printing reduces resource consumption by minimizing water, energy, and chemical usage compared to traditional printing methods (Tilebein 2019). It also minimizes waste generation through on-demand production, eliminating excess inventory and reducing fabric wastage. Additionally, digital printing enables design optimization and sampling through virtual design and simulation, reducing the need for physical sampling and minimizing material waste. The color accuracy of digital printing further enhances ecological sustainability by eliminating the product returns due to printing wrong colors on textile products resulting in less production of waste.

From an economic perspective, digital textile printing brings cost efficiency to the forefront. On-demand production eliminates the need for excessive inventory, resulting in cost savings and reduced material waste. The flexibility of digital printing allows for customization and personalization, meeting the changing demands of consumers and increasing market competitiveness. By enabling shorter lead times and local production, digital printing enhances supply chain control, leading to cost savings and improved speed to market.

DOI: https://doi.org/10.30844/wgab_2023_6

In terms of social sustainability, digital textile printing contributes to enhanced customer satisfaction. The ability to customize and personalize products meets individual customer demands and preferences, fostering greater customer engagement. Microfactories that utilize digital printing, especially when located closer to consumer markets, can ensure shorter delivery times and maintain better control over labor relations, promoting social justice in production.

Integration of digital textile printing and modern online technologies while involving customers in the design process with the help of digital platforms and a digital intermediary of orders not only encourages consumer engagement but also empowers them to contribute to improving social value.

4.2. DTMF with Knitting

4.2.1. Process Description and Technologies

Another textile production workflow that has recently come in the focus of digitalization research is the workflow producing individual knitted textiles, such as knitted shoe uppers, knitted technical textiles, and knitted compression textiles suitable for sports and medical applications. This involves new digitalization concepts in product design and their direct coupling to manufacturing - in this case the knitting machine. In particular, this example of a DTMF can center around manufacturing individualized made-to-measure 2D garments (Šurc et al. 2020) as well as 3D flat knitting and utilizes new technologies that automatically convert scan data or CAD models into knitting patterns.

In other industries, additive manufacturing represents an important driver of innovation. With this manufacturing method, products can be developed and introduced to the market much faster. It already enables cost-effective and automated production of prototypes with minimal resource consumption (Rayna/Striukova 2015, Candia/Beltaguib 2019). 3D knitting as an additive manufacturing process also offers comparable potential due to its flexibility and the possibility of producing final contours directly.

On a flat knitting machine, 3D knitted fabrics with intricate, fully or partially closed, hollow-body-like structures can be produced in a resource-saving and efficient manner (Artschwager et al. 2017). Furthermore, with a 3D knitted surface, the fabrication of constitutive parts of a single product can be saved by knitting them once and all together, which significantly reduces the susceptibility to faults and the time required for post-processing. This has also gained acceptance on the market to the extent that many 3D knitted and, in some cases, individualized products are already being manufactured using this technology (Au 2011). However, conventional processes are characterized by a low level of automation, many trial productions and iterations between models and knitting programs without the possibility of direct interaction between the 3D model, material models and the digital twin of the product (McCann et al. 2016). Consequently, there is a lack of approaches that consider the complete manufacturing processes, starting with the creation of a 3D model, through the effects of material properties on the geometry of the knitted fabric, to global segmentation as the basis for robust algorithmic processing of the 3D model. This gap could be closed with the help of new 3D flat knitting process developed for DTMFs. Based on McCann et al. (2016), Narayanan et al. (2018), Wu et al. (2018), Popescu et al. (2018) and Liu et al. (2020), table 2 highlights the characteristics of both conventional and new 3D flat knitting technologies. In the following, we provide a comprehensive process description of the new 3D flat knitting process.

Conventional 3D flat knitting	**New 3D flat knitting in DTMF**
Limited to specific geometries and materials	Validity for a variety of 3D models and materials
No potential of individualization in production	Potential of individualization at the geometric and material level
Many trial productions and iterations between models and knitting programs	Rapid prototyping without the need for costly preliminary tests
Machine configuration dependant manufacturing system	Automated machine independent manufacturing system
Time consuming development	Low development time
Low degree of innovation	High degree of innovation
Low level of automation	Direct interaction between the 3D model, material models and the digital twin of the product

Table 2: Comparison between conventional and new 3D flat knitting

3D flat knitting is a resource-saving and efficient technology for textile production of 3D geometries. It is considered as a holistic approach across the entire production chain that would enable the application of 3D knitting as a universal tool for textile additive manufacturing and have the potential to revolutionize the knitting industry. This technology approach explores the necessary measures to prepare 3D geometries for the algorithmic generation of knitting programs, develop global segmentation approaches with validity for a variety of 3D models, and create a model to describe different materials. The aim of this technology in a DTMF is to

DOI: https://doi.org/10.30844/wgab_2023_6

develop a machine-independent production system that enables knitwear manufacturers to produce a wide range of products, starting from the 3D model, in small batches or individualized, in an automated and efficient way. In addition to knitwear manufacturers and manufacturers of technical textiles, mechanical engineering companies and software producers can also benefit from this technology.

3D scanning technology, CAD, material science as well as algorithmic processing of geometries represent the building blocks for this digitized manufacturing system for individualized textiles. The individual process components are partially available, their networking is possible in principle and can lead to an efficient overall process. The process model illustrated in Figure 3 links the aforementioned building blocks. The model first considers the creation of the triangulated surface of a 3D geometry. Depending on the material and the machine, the geometry is sampled algorithmically and transferred into a parameter set for the knitting machine. This parameter set is created in such a way that immediate production with the knitting machine is possible. Textile additive manufacturing technology is designed in such a way that the digital twin of the geometry (CAD model or 3D scan) and the material is created in the form of material parameters at the very beginning of the manufacturing process. The geometric digital twin of the product can be derived from the initial geometry by means of an algorithm. All subsequent process steps up to the creation of the knitting program must also be carried out digitally. Only in this way can the data transfer take place quickly and without errors.

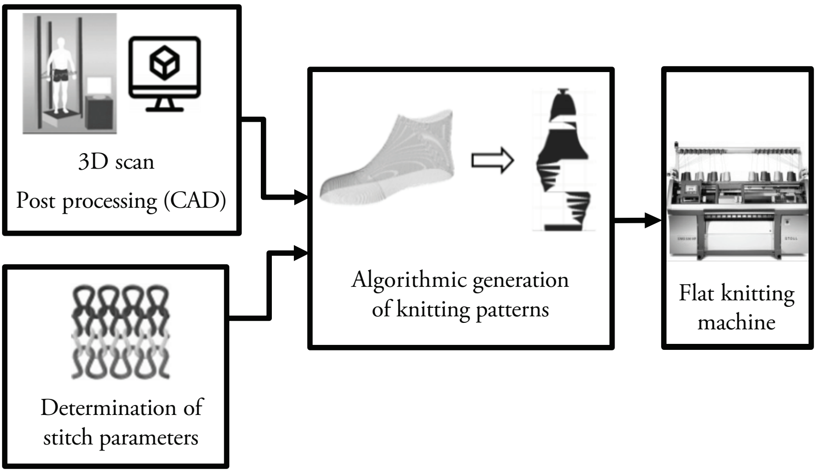

Figure 3: Overview of 3D flat knitting technology in a DTMF (example of knitted upper shoe)

The algorithmic generation of knitting patterns (jaquards) begins with an input mesh with user-specified knitting direction as well as stitch parameters (stitch height and width).

It remeshes the surface to create a row-column graph that represents the knit structure and finally translates it into stitch instructions that are scheduled for a flat knitting machine.

The innovation of this technology lies in the algorithmic interpretation of the 3D geometry as well as systematic holistic consideration of the knitted product, its properties and application, and the integration of these characteristics into the automation solutions. On this basis, production can be designed to be flexible and resource-saving for rapid prototyping and individualization.

4.2.2. Contribution to Sustainability and Social Value

Flat knitting machines are capable of producing near-net-shape finished products, eliminating waste and requiring little to no fabrication in subsequent steps. With the algorithmic processing of 3D geometry into knitting programs, the iterations between models and knitting programs as well as sample production can be largely eliminated. Additive knitting technology thus contributes to resource-efficient and environmentally sustainable production.

The automated creation of jacquards can then enable the development of new products as well as the production of individualized technical knits with significantly less trial-and-error leading to significant savings in production costs in the knitwear industry. The jacquard creation is done in a few minutes, time expenditure is only caused by the configuration of the machine and the production.

Not only can material, costs and time be saved, but at the same time the degree of innovation in product development can be increased by initiating new developments that are not directly based on experience from existing products. Investigating the influence of material properties on the shape of the knitted fabric also contributes to the development of production standards. Existing knowledge is thus systematically and continuously recorded and expanded.

Examples of technical 3D knitted fabrics with high individualization potential such as orthopedic knitted shoe uppers, seat covers for offices and wheelchairs, or therapeutic compression textiles show promising contributions to social sustainability. The potential user group of these knitted products including disabled or patient individuals in need of urgent medical assistance, can benefit directly from this technology when provided with individual service in a short amount of time.

3D flat knitting as a technical approach for individualization offers solutions for previously unaddressed or poorly addressed groups with very special needs which underlines its potential to add to social value.

DOI: https://doi.org/10.30844/wgab_2023_6

5. Summary and Outlook

The textile and clothing industry is facing challenges such as increased customer individualization and the need for flexible value chains. Digitalization offers opportunities for innovation and addresses these challenges. The Digital Textile Microfactory is a flexible production system that enables decentralized manufacturing and on-demand products. It utilizes digital technologies such as digital textile printing or 3D knitting to create a digitally networked design and production process. Regarding its aim to explore the basic concepts and benefits of DTMFs, their impact on sustainability and social value, this paper's findings can be summarized as follows:

DTMFs, compared to conventional textile development and production, show a decent potential for improving sustainability in textile manufacturing. Besides of the economic dimension of sustainability leading to reduced costs and increased innovation in terms of different sustainable business models, there are ecological aspects related to e.g. reduction of waste and transportation needs. Also, the social dimension of sustainability can be improved by e.g. local or regional production being close to the customer. Plus, the DTMF technology itself can serve social value via serving customers with special needs, or use of a digital platform for plug-in micro-services, i.e. a platform whose aim is to include diverse stakeholders in the production process.

Besides having numerous benefits, implementing DTMFs include challenges such as technological aspects that need further development to broaden the range of possible products, difficulty for SMEs to catch up with the digital transformation, the need for new skills and organizational change, evaluation challenges in assessing sustainability potential in detail, and market challenges related to consumer behavior and the risk of rebound effects. Addressing these challenges will require collaboration among stakeholders and a joint industry approach to speed up the process of establishing digital models and case-specific parameters.

Future research could perform a quantitative analysis for each technology in DTMFs in order to provide specific evidence for ecological and economical sustainably of DTMFs and therefore encourage their adoption. Additionally, for supporting the social sustainability and also adding to social value, digital services and platforms could be developed and integrated within DTMFs to support the establishment of larger business ecosystems. Moreover, research is needed to further explore and specify sustainable business models, market trends, and consumer behavior.

More research is underway to address the remaining open questions, and to help these smart, sustainable and socially valuable new technologies thrive.

Acknowledgements

The findings of this paper are partially referring to two research projects:

- The IGF project 20534 N, "Sustainability Potential of Microfactories for Textile Production Networks", funded by the Federal Ministry of Economics and Climate Protection via the AiF within the framework of the program for the promotion of joint industrial research (IGF). The final report of this research project is available from the German Institutes for Textile and Fiber Research Denkendorf (Seibold et al. 2022).
- The IGF project 21996 N, "3D knitting as an Additive Manufacturing Process for the Textile Industry – Development of a Process Model (AddKnit)", funded by the Federal Ministry of Economics and Climate Protection via the AiF within the framework of the program for the promotion of joint industrial research (IGF).

We would like to thank the companies that participated as industrial partners in these research projects, and also all (other) members of the project advisory committee for their kind support.

DOI: https://doi.org/10.30844/wgab_2023_6

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Advancing Medical Resident Scheduling

Improving Human-Centricity in Planning of Medical Education

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1. Introduction

Medical residents are physicians in training who must complete a residency program to become licensed specialists or general practitioners in Austria. The residency program consists of several modules that cover different disciplines related to the chosen specialty. The modules must be completed in specific hospitals that offer duty and training positions for the residents. The process of assigning residents to these positions over a planning horizon of up to 72 months is called residency scheduling. This process is challenging and complex, as it involves multiple stakeholders, objectives, constraints, and preferences. At present, resident scheduling in Austria is mostly conducted manually using generic digital tools such as Microsoft Excel. This leads to high planning effort and inconsistent planning quality for stakeholders, depending on the individual knowledge and skills of the planners. In case of a hospital network analyzed by the authors, 197 working hours are spent each week on training planning for around 200 residents. 52% of these hours are worked by qualified and experienced physicians who are not available for day-to-day hospital operations during this time. The remaining work is carried out by dedicated planning staff, which corresponds to two full-time and one part- time staff working only on the planning and administration of resident training. Automating or at least supporting this planning with algorithms is currently impossible due to lacking available methods. Focusing on the literature, state-of-the-art planning methods for resident training cannot be directly employed due to the specifics and complexity of the Austrian system for resident training, cf. section 2. The main challenge in the Austrian training system is a two-stage allocation of resources, i.e. i) allocating residents to duty and training positions in stations at the same time, with ii) allocations subject to further requirements (e.g. hospital changes, personal preferences , cf. Section 2.1. This considerably enlarges the solution space and requires a planning method tailored to this requirement.

DOI: https://doi.org/10.30844/wgab_2023_7

In related works, exact solution methods using mixed integer programming (MIP) or column generation are applied on much smaller problem instances. Those involve far less constraints and problem features, while still requiring significant computational resources and effort. Using such methods for solving the real-world problem studied in this paper on a large scale would not be reasonable in terms of computational effort and time. To address this problem, this paper proposes a combination of heuristic and metaheuristic methods based on a constructive heuristic and a genetic algorithm (GA) – with GAs being one of the most used method classes for similar planning problems, as demonstrated in Section 2. In a previous approach by the authors, a purely metaheuristic method was applied to the same problem formulation and problem instances (Dummer et al. 2023). However, the metaheuristic approach had limitations concerning runtime performance and solution quality. Pursuing this line of research, this paper deals with the medical resident scheduling problem (RSP), which is a tactical scheduling problem that aims to find a feasible and high-quality schedule for the residents over the entire training period. A hybrid solution method Is proposed that combines a constructive heuristic and a genetic algorithm (GA). Further, two new objectives are introduced to address fairness and equity-related aspects (i.e. variance of the total training duration and consideration of trainee preferences) when scheduling, c.f. Section 4.1. Accordingly, the proposed method is evaluated on real examples and compared with human planning results as well as the earlier method developed by the authors, c.f. Section 5.

The rest of the paper is organized as follows. In Section 2, the relevant literature for the RSP is reviewed. In Section 3, a detailed problem description and a mathematical formulation of the problem is provided. Section 4 discusses the solution methodology developed. Section 5 focuses on validation of the performance of the proposed method. Finally, Section 6 discusses the key findings and provides a research outlook.

2. Related Work

The RSP has been studied in various forms and specifications. This paper analyzes the problem in terms of (i) problem characteristics and (ii) relevant solution methodologies based on a literature review. This literature analysis will be based on Akbarzadeh's comprehensive literature analysis (Akbarzadeh/Maenhout 2021), using a similar analysis structure.

2.1. Characteristics of the problem

Medical resident scheduling is a complex problem because of the stakeholders involved, namely, legislation, hospitals, residents as well as the medical board and medical schools. These stakeholders may have different and conflicting requirements and objectives. An overview of the problem characteristics that have been reviewed in the literature is discussed below.

Legislation and planning complexity: Each country has its own legal framework for medical education. Although there are certain similarities between European medical education systems, it Is practically not affordable to formulate a universal problem. In Austria, there are currently just over 8,300 residents in training. All 271 public hospitals in Austria have a training mandate and perform some degree of resident scheduling. On average, about 30 residents are trained in each hospital. This figure varies greatly depending on the size of the hospital. The largest hospitals train nearly 400-500 residents at a time. The ordinance of the Federal Ministry of Health on "Training to become a general practitioner and a specialist" (Ärzteausbildungsordnung 2015, abbreviated to AO2015) constitutes a set of regulations for the proof of successful completion of practical training in general medical and specialist training. Public medical universities currently offer a total of around 1,540 study places per year in the human medicine program. Currently, about 8,000 graduates are undergoing training to become general practitioners or medical specialists (Bundesministerium für Gesundheit 2022; Rechnungshof Österreich 2021).

Due to almost unique characteristics of national/regional legal framework for medical education, scientific publications usually refer to specific countries or regions. Several publications consider different residency training programs and hospital resources specifically dedicated to them and solve the problem for different programs separately (Kraul et al. 2019; Diponegoro/Rukman 2017 - 2017; Guo et al. 2014). Other papers feature resources shared between different training programs and distinguish between junior and senior students are trained in different programs (Bard et al. 2016, 2017; Proano/Agarwal 2018). Requirements can be adjusted within certain limits (e.g., elective modules) to suit the interests of individual residents, allowing specializations in a particular area (ITO et al. 2018). Few authors modeled direct precedence relationships between two training modules, or disciplines or sections (e.g., is anesthesiology as the basis for general surgery) (Brech et al. 2019). In the case at hand, the training stages (basic and main training) must be planned with precedence relationships, and duty and training positions at the same time.

Hospitals: Hospitals are responsible for the implementation of training programs, i.e., attending physicians supervise residents who are involved in the day-to-day operation of the hospital. As a result, many authors have included staffing requirements in their problem definition. Almost all studies consider a maximum student capacity (Proano/Agarwal 2018; Smalley/Keskinocak 2016). In some cases minimum staffing requirements are included because hospitals count on students as part of the required staff to handle the workload (Guo et al. 2014; Ryan et al. 2013). All above mentioned publications assume that hospital resources are dedicated to a particular specialty. In most cases, minimum and maximum staffing requirements are also specified for a specialty.

DOI: https://doi.org/10.30844/wgab_2023_7

Residents: A limited number of resident requirements are considered in various publications. In most publications, resident requirements play a minor role and are often not even listed as stakeholders. Student availability is a common feature in many studies (Proano/Agarwal 2018; Smalley/Keskinocak 2016). Preferences for a particular specialty were also considered in a few other publications (Diponegoro/Rukman 2017 - 2017; ITO et al. 2018; Smalley/Keskinocak 2016). Other requirements, such as preferences regarding hospitals, departments, or training physicians, were not considered, and must be part of the approach developed in the paper at hand. In addition, to the best of the authors' knowledge, there are no references considering the extent of employment of part-time employees.

Objective function: Several objectives for the RSP can be found in the literature. These objectives differ depending on the considered stakeholders. The following objectives have been already defined: i) provide training that is as fair and equal as possible (Schleyer 1994), ii) carry out the scheduling of all required modules (Guo et al. 2014; Kraul et al. 2019), iii) support the scheduling of all required modules complying with specifications about the training sequence (ITO et al. 2018). In most cases, these training requirements are formulated as hard constraints because of their importance. In addition, Bard et al. (Bard et al. 2016, 2017) consider hospital perspective and minimize violations related to student staffing requirements. Literature shows that objectives related to residents are included in most cases. Smalley and Beliën (Smalley/Keskinocak 2016; Beliën/Demeulemeester 2006) create rotation schedules by making the best use of the availability of residents. Diponegoro (Diponegoro/Rukman 2017) considers preferences for specific modules among other goals. All studies optimize goals of a single stakeholder or at most two stakeholders. To the best of the authors' knowledge, an approach that considers the objectives of all relevant stakeholders involved is not available in the literature.

2.2. Solution Methodology

Finding an exact (optimal) solution (there are multiple optima) to RSP in a real-world setting is very difficult when multiple objectives and multiple requirements are involved. The problem has been shown to be at least NP-complete (Guo et al. 2014), even though Guo et al. dealt with a highly simplified problem with few constraints. Only an assignment to a training and station has been considered. Changes of department or hospital, duty positions, training positions, preferences, etc. have not been considered. In particular, finding an optimal solution for a real-world, large-scale problem requires not only additional computational effort, but also some technical effort, e.g., reformulating the problem or developing special solution methods. The real-world problem at hand, considering the AO2015 and stakeholder interests, is an NP-hard set of problems (Kraul et al. 2019).

The following paragraph gives an overview of the relevant literature of planning methods, with an indication of i) the problem size considered, ii) a categorization of the proposed solution approach, and iii) the computational effort required. Both exact and heuristic methods have been published in the literature are considered.

Several studies propose a greedy heuristic based on decomposition and scheduling individual residents (Diponegoro/Rukman 2017 - 2017; Schleyer 1994). Other authors use mathematical programming and first solve a simpler problem by relaxing some functional constraints or the optimization constraints. Then, they use heuristic methods to optimize further (Franz/Miller 1993; Kraul et al. 2019; Bard et al. 2013). Few publications use exact solution methodology (Bard et al. 2017; Proano/Agarwal 2018; Ryan et al. 2013; Beliën/Demeulemeester 2006, 2007). To solve a large problem instance (i.e., planning many residents simultaneously over a long planning period), some authors reformulate the original problem into a set partitioning problem using Dantzig-Wolfe decomposition (Kraul et al. 2019; Beliën/Demeulemeester 2006, 2007). Column generation is applied to solve the linear programming (LP) relaxation of the reformulated model, and the optimal LP solution is converted to an integer solution using either heuristic techniques or an exact branching scheme. Note that the approaches with an optimal procedure, which requires a significant amount of computational time for large problem instances, contain far fewer problem features and constraints, optimize only a single objective, and are evaluated on instances with few problem dimensions.

Since uncertainties and changed circumstances in scheduling for people cannot be ruled out, re-rostering often occurs after a plan has been disrupted by, e.g. absences due to illness. Maenhout and Vanhoucke (Maenhout/Vanhoucke 2011) describe the problem of reassigning nurses to shifts as a "re-rostering problem", which deals with plans that are invalidated by a change in constraints due to disruptions. The aim of re-scheduling in the context of the RSP is to optimally re-schedule the module that has not been completed while at the same time maintaining most of the existing schedule, to ensure planning security for other residents. In real resident management, rescheduling and postponements occur frequently. To the best of the authors' knowledge, there is no described solution for a resident re-scheduling algorithm in the literature. It is worth noting that Aickelin (Aickelin/Dowsland 2004) uses an approach similar to the one presented. It uses an indirect coding-based approach by creating permutations of nurses with a GA and a heuristic decoder that generates schedules from these permutations. The results are further improved by introducing a hybrid crossover operator and using simple bounds to reduce the size of the solution space. Results show that the algorithm can find high quality solutions while being faster and more flexible than a published tabu search approach. In contrast to the problem at hand, this approach works in the context of short-term deployment planning.

DOI: https://doi.org/10.30844/wgab_2023_7

Akbarzadeh and Maenhout (Akbarzadeh/Maenhout 2021) Introduce a special form of RSP applied in Belgium. They use a heuristic solution procedure consisting of a constructive heuristic and two local search heuristics to optimize the initial solution. The treated RSP corresponds to the Belgian medical training and differs significantly from the practice in Austria, Germany and in particular the USA, where training in hospitals with an exact duration of 12 months must be completed already during the studies. Re-rostering is also not treated. Building on these results, Zanazzo et al. (E. Zanazzo et al. 2022) were able to show that the problem could be solved with a metaheuristic method (i.e. Simulated Annealing) with the same quality but in a significantly shorter time. This evidences that metaheuristic methods have advantages over exact solution methods as problem size and complexity increase, and thus, this will shape a basis for the method development herein.

The authors' investigations also reveal that training quality, fairness or equal treatment are not addressed in the existing optimization literature, i.e. none of the aforementioned planning methods explicitly considers these factors. To sum up, the solutions described in the literature are not affordably and effectively applicable to the complex case of RSP in the Austrian medical education system. In contrast, an optimal solution for the Austrian problem can be transferred to the reduced complexity of other regulations. Hence, the Impact of the approach proposed in this paper can be justified beyond the special case of Austria.

3. Problem definition

This section formally describes the RSP, in which individuals are assigned to a predefined set of medical disciplines (e.g., internal medicine) at multiple hospitals for a period of up to 72 months during their medical training to ensure that they receive adequate medical education. The time unit of month is specified by the AO 2015 and the planning horizon is divided into several sections. First, general practitioners (as well as aspiring specialists) undergo nine months of basic training, followed by actual training in the hospital followed by an internship with an established physician in a certified teaching practice. After basic training, specialists begin basic specialty training and then undergo specialty training in their field. Scheduling must be carried out simultaneously for all people involved, irrespective of their educational progress (i.e., different stages and subjects) as they can possibly be assigned to the same resources. During a given training, residents are assigned to different departments and hospitals, where they work for one or more (consecutive) months under the supervision of an attending physician to ensure that they acquire the required competencies. In particular, the data set was derived from the case of an Austrian hospital organization with 9 hospitals and headquarters in Vienna, Austria, which trains 240-300 residents annually.

Various constraints and multiple objectives related to the three main actors, i.e. legislation, local hospitals and residents, characterize the problem and are described in this section.

Requirements and constraints:

Legislation

The legislation in AO2015 (Bundesministerium für Gesundheit 2022) establishes different educational requirements to ensure that each resident acquires the intended competencies. These requirements are:

- Training should be scheduled in full months.
- Training stages must be completed in the predefined sequence, e.g., basic training before general medicine training.
- Basic training must include both conservative and surgical subjects. Ideally, these should be evenly distributed (e.g. 5 months of conservative subjects and 4 months of surgical subjects).
- Training stages (e.g., general medicine training, specialist training) include a series of educational subjects supplemented by electives that residents may choose from, based on their personal preferences. Successful completion of the training stage requires that all subjects be completed in the defined length and a minimum number of electives be completed.
- Only fully completed electives contribute to overall educational progress; partially completed electives do not.
- Subjects do not have to be completed in one go.
- training can be suspended for a while and continued later.
- Subjects cannot be taken more than once and the duration of training in a subject cannot be extended.
- A person's educational progress is proportional to the extent of his or her employment (half-time employment means half the educational progress of a full-time employee, resulting in a doubling of educational time.).
- A complete training schedule for a particular resident must be compiled at the time a person enters training.

DOI: https://doi.org/10.30844/wgab_2023_7

Hospitals

The set of rules and requirements for planning often vary from hospital (group) to hospital (group) where resident's training takes place. Yet, some scheduling requirements are common in most Austrian hospitals:

- Residents complete training subjects in multiple hospitals, as not every hospital has every medical department needed for training.
- Duty positions are available at different hourly extents, and training positions are available only for 35 hours per week. Both can be shared in different ways among several trainees.
- The resource capacity of the positions may be dedicated to a single specialty or shared across several related subjects.
- A minimum and maximum resident requirement is established for each department and hospital.
- At all times, a resident must be assigned to one or more duty positions that meet their scope of employment. To achieve educational progress, a resident must also be assigned to a training position. Otherwise, this results in a month(s) without training.
- To facilitate planning, department-independent duty positions (i.e., positions that are shared among multiple departments of a certain hospital) can be used as a fallback option if there is insufficient capacity in a department or more training positions have been approved than duty positions.

Residents

In Austria, a resident is a physician in training to become a general practitioner or a physician in training to become a specialist. Their scheduling requirements include:

- Residents can start training at the beginning of any given month.
- Residents can only be trained in disciplines according to their ability (i.e., educational progress and specialty) and when available.
- certain training subjects can be assigned according to preferences.
- Residents may pause, de- or increase their extent of employment at any time.
- The training schedule for the next 12 months must always be known and available to the residents.

Objective Function

All the requirements mentioned so far are specified as hard constraints. The objective function consists of several components that aim to ensure planning quality with respect to the corresponding objectives. To evaluate a resident schedule, the following objectives of the various stakeholders must be considered:

- **Sum** of Months without training, department changes, hospital changes, single month assignments, violated preferences.
- **Variance** of months without training, violated preferences.

Consequently, the objective function considers multiple objectives summed over all residents, i.e. a global sum of negative effects is computed. These summed values are normalized to a range [0,1], with respect to the characteristic sizes of a metric (i.e., total planned months, planned persons, considered preferences) to ensure problem size independence. The variances of negative factors across all residents enforce fairness aspects and equal treatment. This follows the definition of Stolletz and Brunner (Stolletz/Brunner 2012), who define that "fairness can be seen as how violations of preferences are balanced across employees". The objective function is formulated as a weighted sum function, where all individual objectives are considered linearly with appropriate weights depending on a planner's preferences and goals.

4. Method development

The problem dimensions and features considered in this work result in multiple binary decision variables and constraints. As stated in Section 2, a hybrid method of heuristics and metaheuristics Is proposed featuring a greedy constructive heuristic and a GA to provide the scheduling orders for the heuristic. Akbarzadeh and Maenhout (Akbarzadeh/Maenhout 2021) employ a heuristic procedure to solve the RSP relying on a constructive heuristic and two local search heuristics trying to improve the constructed initial solution. In contrast, the method developed herein does not iteratively improve and optimize an initial solution, but rather performs continuous replanning by generating many solutions guided by evolutionary behavior. The constructive heuristic follows all the constraints defined in AO2015 when scheduling residents by mimicking real-world scheduling processes performed by human planners (cf. Section 4.2). The execution of the greedy heuristic for a given input-sequence yields a set of training assignments. Such a training assignment represents the assignment of a person to one or more duty positions and to zero to many training positions for a particular month. These attributes imply the assigned training subject (aka module), the department and thus the hospital. This set of training assignments is in turn used to evaluate the solution's fitness with respect to the previously described objectives.

DOI: https://doi.org/10.30844/wgab_2023_7

4.1. Development of the objective function

Table 1 shows a schematic representation of a scheduling calendar, a 2-D array of assignments that is the basic representation of a training schedule for a given number of residents and time horizon. Each row of the array represents an individual resident's schedule, and each column represents a time period, i.e. a month. Each resident's schedule must contain at least one valid duty position that defines the person's schedule and should contain a valid training position to ensure that the person's training progresses. Duty and training positions can be represented as integers. Therefore, a valid assignment (pi, qj) consists of a tuple of two integers defining the position p_i and the training position q_j occupied by a person.

R/T	**T_1**	**T_2**	**...**	**T_n**
R_1	(pi, qj)	(pi, qj)		(pi, qj)
R_2	(pi, qj)	(pi, qj)		(pi, qj)
...				
R_n	(pi, qj)	(pi, qj)		(pi, qj)

Table 1: Assignments of residents (R) to duty (p) and training positions (q) (Dummer 2022)

Table 2 provides an overview of all components of the objective function considered. The objectives associated with these metrics were identified in collaboration with an Austrian expert and former scheduler in the field of staff scheduling for residents, considering all identified relevant stakeholder interests. Separately, an attempt is made to obtain a holistic view of all related interests as well as fairness aspects in resident scheduling. To ensure minimal training time, it is critical to avoid months without training (MWT). Unnecessary changes between departments (DC) or even hospitals (HC) negatively impact training quality by wasting more training time on administrative and familiarization processes. In addition, more frequent rotations may negatively impact patient outcomes (Denson et al. 2015). Single-month assignments (SMAs) are the worst-case scenario, when it comes to changes of location during training. SMAs are assignments to a specific department that last only one month, so an individual enters and leaves that department in the same month. As described, residents can choose between a few electives in their curriculum, depending on personal preferences. Any preferred subject that is not included in a created plan is considered a violated preference (VP). In the case of long-term absences (e.g. illness) or drop-outs, no training progress is taken into account. The monthly rescheduling examines which months of training have been completed and adjusts the schedule accordingly. The planner is advised to set an interruption period in the system for longer absences, or to remove the person from the pool if the training has been completed.

No.	Metric	Variable	Weight w_i
1	∑ Months without Training	MWT	200
2	∑ Department Changes	DC	50
3	∑ Hospital Changes	HC	500
4	∑ Single Month Assignments	SMA	500
5	∑ Violated Preferences	VP	50
6	Variance of MWT among residents	V-MWT	5
7	Variance of VP among residents	V-VP	5

Table 2: Metrics used in the objective function.

To satisfy the residents' need for fairness and equal treatment, two additional metrics have been added in this paper, each assessing the variance, i.e., the equal distribution of negative aspects of planning. This approach is discussed more often in research on workforce scheduling and is also known, for example, in the scheduling of train drivers, i.e. unpopular routes or shifts are distributed as equally as possible among all drivers (Jütte et al. 2017). When creating a shift plan with multiple objectives, the pursuit of equity is usually accompanied by a deterioration in other objectives, such as cost or efficiency. For the present planning case, the two metrics are i) the variance of months without training (V-MWT) and ii) the variance of violated (preferred subject) preferences (V-VP) among the trainees. The weighting of the individual goals is currently subject to a planner's strategy . The weights used in the objective function (c.f. Table 2) were determined experimentally in collaboration with a planning expert and iteratively refined in the evaluation process. Accordingly, the optimization problem consists of 17 stakeholder requirements, 7 objectives considered for evaluation and is formulated as a minimization problem. The objective function is shown in Equation 1.

$$O(\mathrm{x}) = \sum_{i=1}^{7} f_i\,(\mathrm{x}) \times w_i$$

Equation 1: Objective function.

The associated objective function f_i for each individual objective (c.f. Table 2) is defined on x, which is the mathematical representation of a training schedule (i.e. set of training assignments). The corresponding weight for a particular objective is denoted with w_i.

4.2. Optimization method

In this section, the development of the planning method is described. In the optimization process, a GA modulates the order in which a greedy heuristic schedules the necessary training modules for all residents. This approach is inspired by Aickelin (Aickelin/Dowsland 2004) who presented a similar approach to solve the Nurse Scheduling Problem, which deals with short-term operational scheduling. To enforce elitism concerning the considered objectives, all six individual goals and $f_i\,(\mathrm{x})$ are used as criteria for a non-dominated sorting survival mechanism proposed by Deb (Deb et al. 2002). The selection operator (i.e. tournament selection), utilizes the value of $O(\mathrm{x})$ (c.f. Equation 1). The consideration of the objective function, comprising all previously defined weights w_i , in the selection operator, allows for user-specific customization of the algorithm by introducing bias to the selection process. Thus, it gives control over the planning process with respect to prioritization of specific objectives. To maintain diversity in the population of the GA, a population size of $\mu = 40$ is used, which was determined experimentally considering convergence speed, overall obtained solution quality and runtime. Populations of this size have been shown to provide sufficient robustness for computationally intensive evaluation functions in multimodal search spaces (Kamhuber et al. 2020).

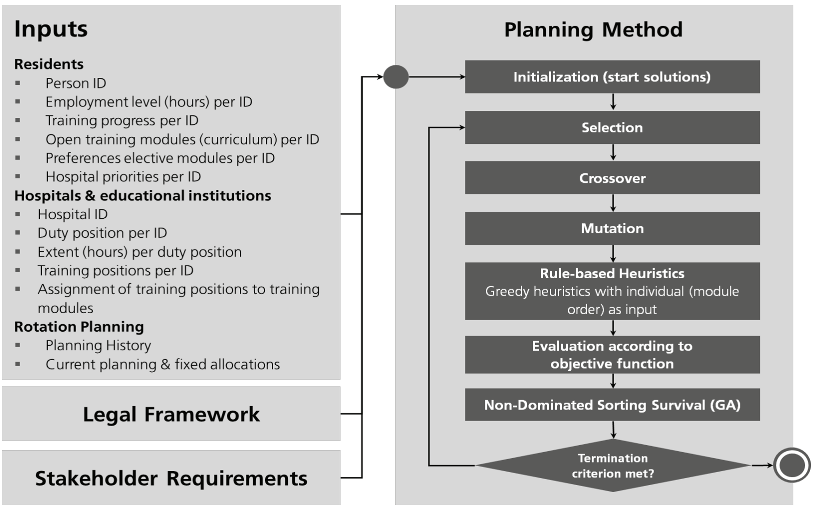

Figure 1: Flowchart of the presented planning method

A general overview of the algorithm's operating principle is shown in a flowchart in Figure 1. Initially, a set of integers, containing all necessary training subjects for all considered residents, is created. Initial solutions for the algorithm are obtained by creating randomly shuffled vectors from said set. Those vectors are the genotypes of the Individuals of the GA. The genotype of an individual determines the order in which the greedy scheduling algorithm plans each module. Thus, the optimization problem solved by the GA is a permutation problem of a 1-dimensional vector. The algorithm uses a simple swap mutation operator, and no crossover operator is used as it did not prove to be beneficial in experimental studies. The genetic algorithm used can be classified as similar to the NSGA-II (Deb et al. 2002) due to its survival mechanism. After creating new individuals by selecting parents and applying the genetic operators to them, individuals are evaluated by passing their genotype to the greedy scheduling heuristic. This rule-based heuristic initially applies a simple repair algorithm that reorders the list of integers to prevent infeasible planning solutions (i.e., sequence violations). After repairing the input list, the heuristic schedules each listed training module sequentially by greedily selecting the best of the remaining combinations of training and duty positions. In this case, "best" means the algorithm tries to prevent department or even hospital changes at all costs. Notably, a person will only switch departments or hospitals if necessary. A month without training is only assigned if there is no free combination of training and duty position available. After the planning process for each genotype is completed, the created plans are evaluated using the objective function and the obtained objective values are returned and assigned to the individuals of the GA. A new population is formed by applying the non-dominated sorting mechanism to the newly created population and the previous one. The process terminates, once the specified termination criterion is met (i.e., number of generations or convergence of fitness).

5. Computational Study

This section provides computational insights into the proposed method. Further, It carries out a benchmark comparison with the results of the previous GA-only approach by the authors (Dummer et al. 2023) (hereafter referred to as GA-method) and a reference solution created by a human planning expert. The proposed algorithm was implemented in Python and Rust, and all tests were performed on a Core i7-10510U CPU, 16 GB of RAM and Ubuntu 22.04 LTS. The test dataset is based on anonymized data that has been enriched with additional information such as preferences and absence times. It contains 78 residents and 5 hospitals. The dataset is the same as in (Dummer et al. 2023). When enriching the test dataset with preferences, the final schedule was used to retroactively assign preferences, i.e., the reference solution is optimal concerning VP. Thus, this reference solution is harder to beat.

The comparison of the three schedule, namely expert solution, GA-method and proposed method is shown in Figure 2. Note that the original objective function (i.e., without the variance metrics) from the GA-method is used to establish a fair comparison of the three methods. The achieved objective-function values of the expert solution (40.98) and the GA-method (81.53) are plotted as horizontal dashed lines. The vertical dotted line indicates the maximum number of objective-function evaluations performed in (Dummer et al. 2023). The proposed method outperforms the GA-solution after a few generations and the expert's solution is surpassed after around 1,000 generations. After 50,000 generations an objective-function value of 17.81 is achieved, but already after 20,000 generations a value of 20 is reached. The expert solution is outperformed by the solution method presented in all single objectives except, unsurprisingly, for the violated preferences (VP) (c.f. Figure 3). In Figure 3, all other objective values almost immediately surpass the expert's solution in terms of quality, only the improvements regarding personal preferences take more time.

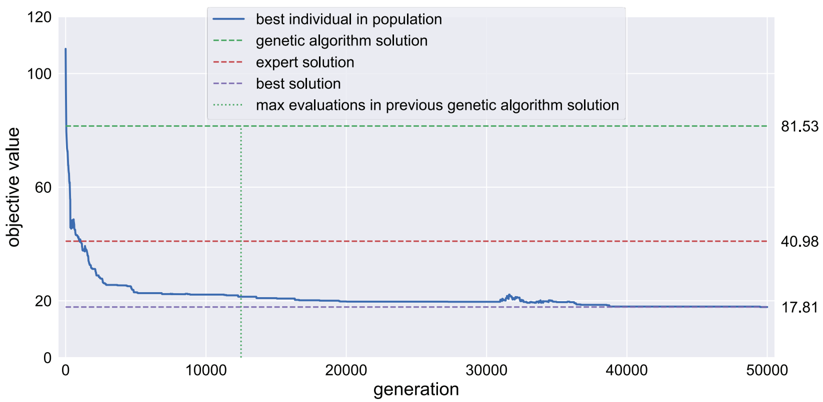

Figure 2: Benchmark: proposed method vs. previous GA method vs. expert solution

Table 3 compares the runtimes of the GA-method and the hybrid method presented and shows the influence of the population size for the hybrid method. The differences in runtime can be explained by the efficient design of the planning method and the use of the Rust programming language compared to Python. For an optimization run of 50,000 generations with a population size of $\mu = 10$, the Python-based GA-method requires 4,200 minutes, while the presented hybrid solution requires only 235 minutes. Thus, the older method is almost 18 times slower than the presented method. This value could be further reduced by using more powerful hardware. Since the new planning method generates better solutions than the expert and the GA-method after only 1,000 generations, good schedules can be generated within one minute. However, this value will increase with the size of the solution space (i.e., more residents, hospitals etc.). The exact time spent to create the manually compiled expert solution has thus far not been recorded. In particular, a few hours were reported.

Method	**Pop Size**	**500 Gens [s]**	**50.000 Gens[min]**	**Runtime /Gen [s]**	**Runtime/ Individual [s]**
GA	10	252	4200	0,504	0,0504
Hybrid	10	14.11	235,17	0.028	0.0024
Hybrid	40	34.63	577.23	0.069	0.0017
Hybrid	100	69,76	1162.63	0.140	0,0014

Table 3: Runtime comparison

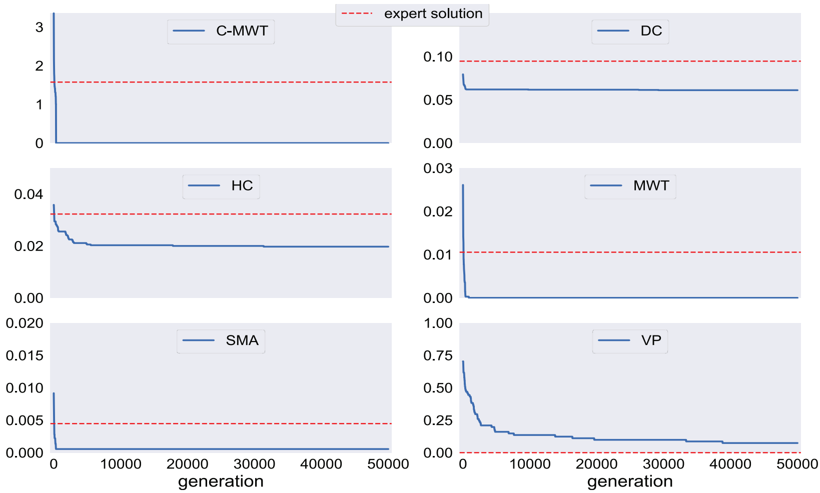

Figure 3: Benchmark normalized single objective values - proposed method vs. expert

The new objective function no longer takes consecutive months without training (C-MWT) into account because the metric had a negative impact on the optimizers efficiency and is rendered obsolete due to the introduction of V-MWT. The resulting function value reaches its minimum at 16.46. Thus, even with two additional objectives and otherwise the same weights as in the prior objective function, the optimization method can find even better solutions than before. In addition, the proposed method performs better in terms of convergence speed when using the newly introduced objective function (compare Figure 2 and Figure 3) almost reaching the final fitness value after about 13,000 generations.

DOI: https://doi.org/10.30844/wgab_2023_7

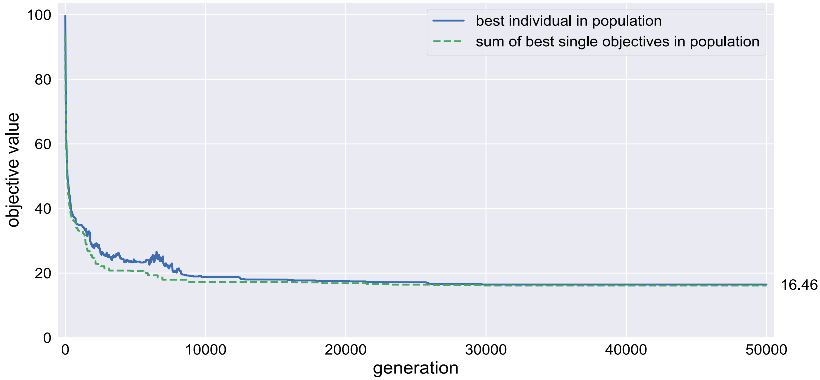

Figure 4: Objective function value of the proposed method with proposed weights

Figure 5 shows the qualitative evolution of the part goals of the new objective function over time for 50,000 generations, each normalized on a range [0,1]. The objective values MWT, V-MWT, SMA and DC and drop almost immediately to their final value. The other objective values converge more slowly towards their optimum.

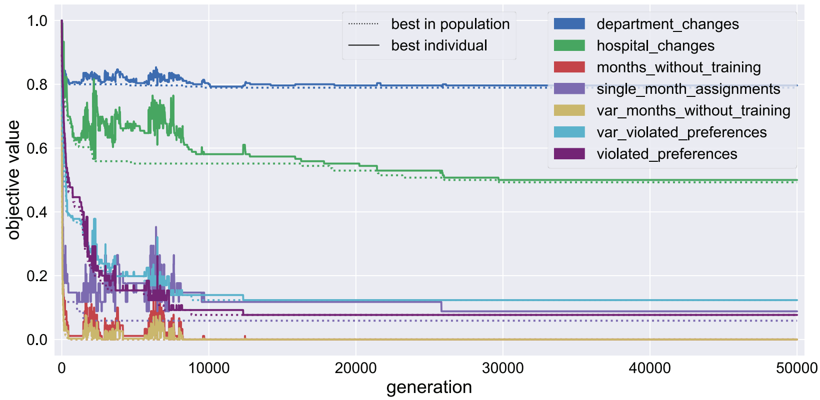

Figure 5: Single objective values for the new configuration of objectives (normalized)

HC, VP and V-VP reach their final value after around 10,000 generations but continue to gradually improve until 30,000 generations. For SMA, some improvement can be seen until just over 25,000 generations, after remaining on a plateau for most of the optimization.

6. Discussion & Outlook

This paper shows that a hybrid optimization method with an indirect GA and rule-based heuristics is suitable to solve a complex RSP and to generate solutions with high planning quality in a short time. At the same time, it was demonstrated how fairness and equity for the residents can be better pursued by extending the objective function with variance metrics. It could successfully be demonstrated that the method achieves solutions with higher quality than human schedulers. The proposed method can potentially reduce the planning effort and improve the planning quality for hospitals by (semi-)automating or supporting the scheduling process. It can also potentially increase the satisfaction and motivation of residents by considering their preferences and ensuring fairness in their training.

Despite merits, the proposed approach faces some limitations concerning the method evaluation and real-world testing, which Identify the pathways for future research. In particular, the criteria of the objective function used in this paper have not yet been finalized. In the next step, the exchange with residents (as target groups) will be intensified to define and better evaluate further aspects of fairness and thus to refine the objective function. According to an initial survey, a final objective function with 12-13 criteria is envisaged. It could make the solution finding more difficult to calculate but will provide solutions with better quality and better acceptance by all stakeholders. Integrating feedback or evaluation (from planner and residents) mechanisms into the solution methodology to track and improve the training performance of residents could be one way to implement this. Another requirement for the solution is that existing schedules should only be changed slightly, especially for the near future, in the event of a rescheduling. This would significantly increase planning reliability for residents, as no major changes would be expected during monthly rescheduling. Also, while the dataset used is already quite large, real-world planning problems from larger hospitals or hospital groups can be more extensive. Hence, in the next step the efforts are extended to a validation with real-world use cases and additionally comparing the plans with existing manual planning from hospitals. Possibilities for employing this approach in strategic workforce planning will also be investigated. Currently, the approval process for new duty and training positions is not transparent, and it is usually not known where these positions are missing to achieve better planning quality. With an extension of the proposed method, it would be possible to search for optimization potentials through new positions by including fictitious additional positions in the planning process. Investigating possible benefits of transferring the method developed for the complex Austrian regulations to other countries and possibly related planning problems will be another research trajectory.

Finally, yet importantly, a further research direction is to use machine learning or artificial intelligence (AI) methods for optimization. One option is to use data-based methods that learn from data, based on manually obtained planning

DOI: https://doi.org/10.30844/wgab_2023_7

outcomes. However, this may introduce bias and limit the solution quality to human performance. Another option is to use learning algorithms such as deep reinforcement learning, which could train on a digital model – similar to the one used for the GA and heuristic – before the actual planning, and then execute it faster with a learned strategy. This poses challenges in terms of explainability and responsibility (i.e. fairness, equity, inclusiveness), as well as dealing with the complexity of the search space.

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Navigating Ecosystem Virtuality

An Integrative Perspective on Digital and Colocated Collaboration for Innovation

Robert Rose, Valeska Maul, Katharina Hölzle, Wilhelm Bauer

1. Introduction

Addressing future challenges by means of innovation requires organizations to work together to a much larger degree than today, requiring both physical ('colocated') and digital collaboration. This collaboration for innovation often goes beyond single organizations and results in networks of shared value creation of different actors such as companies, research institutions, or supporting actors. These ecosystems of innovation transcend geographical and organizational boundaries and are enabled by the use of virtual tools. Consequently, activities between actors in *innovation ecosystems* comprise colocated as well as digital collaboration – or coined differently, involve both 'bricks & clicks' (Klimas/Czakon 2022).

The hybrid nature of collaboration in ecosystem-based innovation efforts is unsurprising given the complexity stemming from various interdependent elements such as actors, activities, artifacts, institutions, and the dispersed relations among them (Granstrand/Holgersson 2020). Technological innovation, in particular, requires the collaborative elaboration of diverse expertise and resources rarely colocated in one physical place. For instance, Mazzucato and Robinson illustrate how NASA's decades-long shift in the low-earth-orbit industry from being integrated in-house toward a dispersed multi-actor ecosystem has paved the way for innovation (Mazzucato/Robinson 2018), encompassing the use of virtual tools as well as colocated interactions (Mazhari et al. 2017). In fact, today's status quo of inter-organizational work regularly involves the converging use of virtual tools in the form of enterprise social media, enterprise resource planning systems, cloud-based collaboration tools, project management solutions, or shared digital twins.

The recent global pandemic has further catalyzed digital collaboration in innovation ecosystems, notwithstanding the geographical proximity of its actors, and in the process, exposed the benefits and pitfalls of virtual tools (Faraj et al. 2021). A crucial ensuing question for ecosystem actors that we follow in this article then pertains to a potential balance between colocated and digital collaboration, and equally important, how this spectrum can be conceptualized and operationalized.

DOI: https://doi.org/10.30844/wgab_2023_8

Several distinct streams of literature offer initial insights for a continuous understanding of colocated and digital collaboration. First, the notion of *connectivity* (Kolb 2008) and *socio-materiality* (Orlikowski/Scott 2008) provide theoretical grounds for the presumption that the use of technology in and around organizations should be viewed on a spectrum and not in dichotomous terms (e.g., face-to-face vs. digital). Second, more specific frameworks in management literature regarding *virtual work* (Raghuram et al. 2019) or *digital internal communication* (Wuersch et al. 2023) give nuance to the involved levels of analysis and related concepts (e.g., digital platforms in organizations). Third, the multi-dimensional concept of *virtuality* (Kirkman/Mathieu 2005) in organizational literature falls into this tradition and has found repeated empirical application, however, mainly at the team level (Purvanova/Kenda 2022). Fourth, and lastly, ecosystem-specific research remains vague about the role of digital technologies for, in, and from ecosystems and resorts to discrete representations in terms of *digital innovation ecosystems* (e.g., Wang 2021) or *regional innovation ecosystems* (e.g., Radziwon et al. 2017). Taken together, each research stream affords a valuable perspective in itself, yet with no concept available that can be applied at the ecosystem level which allows for a continuous view (i.e., degrees) of employing virtual tools across actors.

Our article is set out to capture the spectrum between colocated and digital collaboration in innovation ecosystems by introducing the concept of *ecosystem virtuality*. Specifically, we translate the established concept from research on team effectiveness to the ecosystem level and look at the degree of *technology dependence*, in*formational value*, and *temporal dispersion*. Following the seminal works of Kirkman and Mathieu (2005), we define ecosystem virtuality as *the extent to which ecosystem actors rely on virtual tools to engage in collaboration, the amount of informational value provided by such tools, and the temporal dispersion of actors' collaboration*. Furthermore, we integrate related but so far disjointed insights from the literatures of organizational studies, ecosystem research, as well as technology and innovation management. Upon this integrative perspective, we propose key antecedents of ecosystem virtuality such as geographical dispersion, boundary conditions such as the level of trust among actors, and how these factors influence innovation.

Our conceptual contribution offers a pathway to operationalize and measure the degree of colocated and digital collaboration beyond single organizations, and therefore, allows for future empirical work to investigate potential optima of virtuality in innovation ecosystems. A resulting degree of ecosystem virtuality is independent of the specific tools in use and can thus account for the rapidly evolving landscape of virtual tools in (inter-)organizational practice. Assessments of ecosystem virtuality will enable the involved actors to make better-informed decisions for adequate means and modes of virtual tools for ecosystem-wide collaboration. For instance, ecosystem infrastructure such as *innovation hubs* (Haukipuro et al. 2023) can be set up physically, virtually, or in between, and emerging ecosystem instances of the so-called *industrial metaverse* are interfacing the physical and digital space by design while the scope of applications is still evolving (Li et al. 2023).

In perspective, knowing and understanding the *degree* of virtual tool use among actors in an innovation ecosystem is imperative for its involved actors to find a balance when collaborating in the physical and digital world.

The remainder of this article is structured as follows. In the subsequent section, we establish the theoretical premises and relatives of ecosystem virtuality. Next, we conceptualize ecosystem virtuality along its three dimensions, i.e., technology dependence, informational value, and temporal dispersion. We follow this with an integrative perspective on relevant antecedents, boundary conditions, and how ecosystem virtuality relates to innovation. Finally, we discuss the potential implications and directions for future research ahead of our concluding remarks.

2. Differentiating Theoretical Backgrounds

Understanding collaboration in innovation ecosystems as a convergence of virtual tool use and colocated interactions invoke distinct streams of research. In what follows, we draw from several research disciplines related to this phenomenon, first, by outlining the influence of digitalization on innovation ecosystems, and second, by describing the concept of virtuality from organizational literature.

2.1. Innovation Ecosystems in Digital Contexts

In complex business environments, the pursuit of innovation has transitioned from the solitary endeavor of individual organizations to a collaborative effort characterized by complex relationships among multiple actors. The increasingly decentralized and networked nature of innovation is reflected by the popularized metaphor of *ecosystems* in management research and practice (Adner 2006; Cobben et al. 2022). Specifically, *innovation ecosystems* are commonly defined as "the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors" (Granstrand/Holgersson 2020, p. 3).

The boundaries of innovation ecosystems develop from a joint "value proposition through collaboration" (Autio/Thomas 2022, p. 17). Collaboration in this context can be understood as mutually supportive interactions (Castañer/Oliveira 2020). The specifying qualifier 'digital' primarily involves the use of virtual tools irrespective of the actors' geographical locations (e.g., cloud-based communication suites), and 'colocated' refers to collaboration occurring within close physical proximity without using virtual tools (e.g., co-working spaces). However, this distinction has become blurred in ecosystems due to the all-pervasive and advancing plethora of virtual tools.

DOI: https://doi.org/10.30844/wgab_2023_8

Digitalization has had a profound impact on innovation ecosystems. Prominently discussed influences include *digital innovations* embedded within and stemming from ecosystems (e.g., Nambisan et al. 2019; Wang 2021) as well as the evolving *governance and orchestration* of ecosystems (e.g. Hölzle et al. 2022; Kindermann et al. 2022). Related research on collaboration in *inter-organizational relationships* (Majchrzak et al. 2015) provides a complementary perspective, e.g., concerning virtual collaboration effectiveness (Zhang et al. 2018) or information sharing practices (Lee et al. 2021).

Despite manifold insights into these topics, previous research has fallen short of addressing the implications of virtual tools for *ecosystem-wide collaboration*. Recent reviewing works on the digital transformation have therefore emphasized the need for future research at the ecosystem level in this regard (e.g. Dąbrowska et al. 2022; Vial 2019). A potential reason for the previous paucity of ecosystem research on digital collaboration and related concepts such as communication, coordination, or cooperation (Castañer/Oliveira 2020) lies in more apparent levels of analysis such as teams, projects, organizations, or platforms. However, given that actors coalesce around a shared value proposition in innovation ecosystems, collaboration is not bound to these levels but happens across and between them, enabled by virtual tools.

2.2. Virtuality in Theory and Empirical Research

Virtuality implies a ubiquitous influence of digital technologies for collaboration, theoretically informed by the perspectives of connectivity, socio-materiality, and socio-technical systems. Each strand contributes an important aspect to our theoretical perspective on virtual tool use in ecosystem collaboration practice.

In organizational studies, *connectivity* refers to "a metaphor that highlights the complexities, interconnected processes and synchronized activities" (Angwin/Vaara 2005, p. 1448) of interactions within and across organizations, incorporating a social and technical dimension (Kolb 2008). Important for the context of dispersed ecosystems, research on connectivity gives insight into potential tensions and paradoxes (Kolb et al. 2020), thereby suggesting an *optimal degree* of virtuality which spans organizational and geographical boundaries.

The closely related notion of *socio-materiality* emphasizes how social and technological phenomena are inseparable in today's organizational reality of digitally-enabled work practices (Orlikowski/Scott 2016). At an aggregate level, the adjacent term *socio-technical system* is defined as the "[r]ecursive (not simultaneous) shaping of abstract social constructs and a technical infrastructure that includes technology's materiality and people's localized responses to it" (Leonardi 2012, p. 42). Scholars across disciplines have employed the socio-material and socio-technical lens to abstract our comprehension of the human-technology relationship toward generalizable mechanisms and patterns.

For instance, Malhotra and colleagues recently curated a special issue on the topic of 'socio-technical affordances for large-scale collaborations,' concluding in their introductory review that "research needs and insights related to technology-enabled forms of large-scale organizing will grow in the coming decade" (Malhotra et al. 2021, p. 1388).

Virtuality research so far has been focused on empirically validating the concept in teams and organizations (Raghuram et al. 2019), laying the groundwork for a further translation to ecosystems.

At the team level, research conceptually shifted from categorizing teams as virtual vs. colocated to degrees of virtuality (Dixon/Panteli 2010), "given that most organizational teams can to some extent be considered virtual" (Gilson et al. 2015, p. 1317). A widely adopted definition introduced by Kirkman and Mathieu depicts virtuality along three dimensions as "the extent to which team members use virtual tools to coordinate and execute team processes, the amount of informational value provided by such tools, and the synchronicity of team member virtual interaction" (Kirkman/Mathieu 2005, p. 700).

Meta-analytic findings show that team virtuality features a curvilinear relationship with information sharing (Mesmer-Magnus et al. 2011), that virtuality positively moderates the relationship between the level of trust and effectiveness in a team (Breuer et al. 2016), but also, that team virtuality does not directly predict team effectiveness (Purvanova/Kenda 2022). In essence, while virtuality plays a substantial role in teamwork, its influence on team effectiveness is mixed and contingent on several other factors. This ambivalent role of virtuality for teams prompts Purvanova and Kenda (2022) to point to the *virtuality-as-paradox* perspective (see also Purvanova/Kenda 2018), acknowledging the simultaneous benefits and pitfalls of virtual tool use.

At the organizational level, virtuality has been discussed only tangentially in the context of *virtual organizations* (e.g., Shekhar 2006). Riemer and Vehring (2012) observe an incoherent body of knowledge and use of the term virtual organization, but identify defining criteria such as a project orientation, focus on value creation, and a prevalent network structure. The authors further classify types of virtual organizations, of which the closest resemblance to ecosystems can be found in 'networked virtual organizations' (Riemer/Vehring 2012). Accordingly, the networked virtual organization is characterized by a collaborative inter-organizational network of actors who realize synergies linked through virtual tools, and interestingly, *trust* as "the key enabler of collaboration, which points to the importance of social relationships in the network" (Riemer/Vehring 2012, p. 272).

Bringing together the above, the concept of virtuality builds upon rich theoretical strands which share the premise that digital technologies and collaboration have become inseparable over the last decades and can result in paradoxical tensions.

DOI: https://doi.org/10.30844/wgab_2023_8

The empirical focus has been the team level of analysis with findings indicating important contingent factors such as trust. We build upon these insights for our following conceptualization of ecosystem virtuality.

3. Conceptualizing Ecosystem Virtuality

In this section, we define virtuality as an aggregate property of ecosystems and elaborate on its underlying three dimensions based on the foundational works of Kirkman and Mathieu (2005). Accordingly, we define ecosystem virtuality as *the extent to which ecosystem actors rely on virtual tools to engage in collaboration, the amount of informational value provided by such tools, and the temporal dispersion of actors' collaboration*.

It is worth noting that there is no general scholarly consensus on the dimensions of virtuality, reflecting its various manifestations in different contexts at different levels. Nonetheless, Raghuram et al. (2019) and others have identified technology dependence, temporal dispersion, and an informational facet as commonly adopted core dimensions of virtuality (see also, Bell et al. 2023). Discrepancies mainly arise from the question of whether *geographical dispersion* qualifies as a dimension. We concur with Foster et al. that "[p]eople/teams that are co-located may use technology-mediated communication just as much as distributed people/teams" (Foster et al. 2015, p. 281). This renders geographical dispersion as an important antecedent of virtuality but not as an inherent definitional component (see also, Section 4.1). Further, inconsistencies in the literature usually stem from a context-specific empirical construct (e.g., for meta-analytic purposes) but commonly share the underlying premises of the theoretical concept. For our definition of ecosystem virtuality, we adhere to established conceptualization practice as outlined by Podsakoff et al. (2016) and elaborate on its underlying three dimensions in the following.

3.1. Technology Dependence

Knowledge-intensive collaboration has become inseparable from using virtual tools. The recent global pandemic has certainly accelerated and amplified this trend and led to the adoption of digital technologies at an unprecedented pace and scale (Amankwah-Amoah et al. 2021; Faraj et al. 2021). Despite evolving sentiments (e.g., technostress) or task-specific differences (e.g., remote work), the reliance on digital technologies represents an inherent definitional feature of virtuality (Raghuram et al. 2019). Technology dependence has previously been specified as the *extent* of using technology-mediated interactions in terms of its proportion to face-to-face interactions, operationalized by the relative *frequency* of use (e.g., Mesmer-Magnus et al. 2011; Schaubroeck/Yu 2017).

An ecosystem-wide dependence on technology for collaboration will be highly specific to the respective context and depend on other factors such as the nature of predominant tasks, or the availability of digital and physical infrastructures (for our discussion of boundary conditions see Section 4.3). Further, different ecosystem actors and subsets of actors will exhibit varying degrees of technology dependence. Still, the overall degree to which actors of an ecosystem rely on digital technologies in their collaboration toward joint value creation can be reflective of an aggregate level of ecosystem virtuality. This becomes evident in practice with regard to boundary-spanning collaboration spaces such as innovation hubs (Haukipuro et al. 2023). Certainly, technology dependence will be closely related to the means and modes of interactions which is captured by the following dimensions of virtuality.

3.2. Informational Value

The informational value conveyed among collaborating actors emanates from the richness of information – e.g., text messages generally have a lower value, extended reality (XR) environments have a higher value, and face-to-face interactions typically hold the highest value. However, as Kirkman and Mathieu (2005) argue, informational value is eventually determined by how means of collaboration are adequate to the task at hand. As an example, engineers collaborating in the additive manufacturing industry would not benefit from discussing design models face-to-face but require CAD tools to this end (Kirkman/Mathieu 2005). Consequently, virtuality is also reflected by the characteristics of how information is conveyed, insofar that more valuable information results in lower levels of virtuality.

The overall extent of informational value conveyed in an ecosystem would represent the richness and adequacy of a host of involved virtual solutions and face-to-face exchanges, and therefore, reflects an important qualitative facet of overall virtuality. Although Raghuram et al. note that "such a nuanced approach to measuring virtuality is still rare in empirical virtual teams research" (Raghuram et al. 2019, p. 320), an operationalization at the ecosystem level could comprise assessments of subjective perceptions or an objectified index of the tools in use.

3.3. Temporal Dispersion

The temporal dispersion (also, 'synchronicity') of collaboration has become an omnipresent consideration for modern workplaces – e.g., when working from home, abroad, or when deciding to use a 'synchronous' face-to-face meeting or an asynchronous e-mail. Thus, this dimension of virtuality takes into account the extent of temporal dispersion between real-time and time-lagged modes of collaboration. Similar to the other dimensions it hinges on several context factors such as geographical dispersion, work schedules, or the nature of the task (Raghuram et al. 2019).

DOI: https://doi.org/10.30844/wgab_2023_8

An ecosystem-wide assessment of temporal dispersion holds important insight into the functioning of the ecosystem, that is, the resulting composite could give indications of predominant preferences regarding the communication culture among actors. For instance, more asynchronous collaboration practices would contribute to higher levels of overall virtuality regardless of geographical proximity.

4. Integrating Ecosystem Virtuality

We integrate concepts related to the emergence of ecosystem virtuality in a conceptual framework by drawing from virtuality and ecosystem literatures. An overview of the suggested antecedents, boundary conditions, and consequences is shown in Figure 1. In the following, we particularly highlight *geographical dispersion* as a determining antecedent of ecosystem virtuality, focus on *innovative performance* as the key consequence, and outline *trust* as a boundary condition that could shape the influence of virtuality on an ecosystem. Notably, we focus on these concepts at an aggregate level, however, each of which are multi-level by nature (e.g., trust) which holds implications for subsequent research designs.

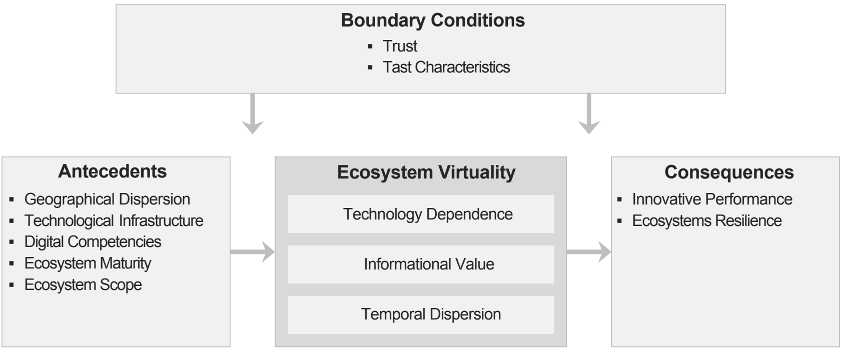

Figure 1: A Conceptual Framework of Antecedents, Consequences, and Boundary Conditions of Ecosystem Virtuality

4.1. Antecedents

Innovation ecosystems commonly comprise actors that contribute to a joint value proposition in spite of their geographical location. At the same time, innovation ecosystems often feature colocated actors such as in science and technology parks (Sandoval Hamón et al. 2022), and corresponding research on territorial innovation offers a wealth of insights into the benefits of spatial proximity (e.g., Howells/Bessant 2012). However, the post-pandemic work reality has become less bound to traditional conceptions of workplaces (Leone 2023), and thus, substantially increases spatial flexibility by leveraging virtual tools (Haefner/Sternberg, 2020). In one way or the other, we contend that *geographical dispersion* represents a crucial determinant of ecosystem virtuality. We thereby follow previous lines of reasoning that geographical dispersion does not qualify as a definitional component of virtuality (e.g., Foster et al. 2015). For instance, colocated actors (e.g., an office apart) as much as distant actors (e.g., a continent apart) could equally rely on virtual tool use. Still, geographical distance can be indicative of higher levels of virtuality, and thus, constitutes an important and meaningful antecedent of ecosystem virtuality. Operationalizations of geographical dispersion in innovation studies usually entail network measures and have been applied in the study of innovation ecosystems as well (e.g., Still et al. 2014).

Several further contextual factors and characteristics of an innovation ecosystem should be considered as antecedents of its virtuality (for a similar rationale in teams, see also Kirkman et al. 2012; Kirkman/Mathieu 2005). In particular, *technological infrastructure* is essential for ecosystem virtuality, comprising the availability, access, and affordability of high-speed broadband networks (Lynn et al. 2022). Better technological infrastructure could eventually lead to lower levels of virtuality given the omnipresence of video-conferencing or progressing adoption of collaborative XR environments (see also Section 5.2). Furthermore, the level and distribution of *digital competencies* among ecosystem actors play a key role in realizing the potential of virtual tools (Oberländer et al. 2020). With respect to the characteristics of innovation ecosystems, their *scope* (e.g., in terms of their number of actors), and state of *maturity* are likely to influence their level of virtuality. Conceivably, innovation ecosystems that have progressed in their evolution could resort to higher degrees of virtuality subsequent to a formation phase (Dedehayir et al. 2018) which would require more colocated collaboration.

4.2. Consequences

The arguably most relevant outcome of an innovation ecosystem pertains to its collective *innovative performance* (Gomes et al. 2018; Granstrand/Holgersson 2020). This is typically assessed by the novelty, usefulness, and frequency of product, service, process, or systems innovations. We submit that the innovative performance of an ecosystem is substantially influenced by its aggregate level of virtuality. Furthermore, we argue that ecosystem virtuality and innovative performance exhibit an inverted U-shaped relationship, suggesting an optimum degree of virtuality. A theoretical rationale for this relationship can be found in the virtuality-as-paradox perspective (Purvanova/Kenda 2018), implying simultaneous challenges and opportunities arising from the use of virtual tools. For instance, Purvanova and Kenda (2018) illustrate this for team-level technology dependence in the form of 'touch tensions' (impersonal vs. less-biased interaction), 'data tensions' (data overload vs. informed decisions), and 'task tensions' (constant stress vs. intriguing work). This would also hold true in ecosystems, where on the one hand a lack of virtuality is often not feasible, and on the other hand, an over-pronounced use of virtual tools contradicts the collaborative co-creation of value in ecosystems.

DOI: https://doi.org/10.30844/wgab_2023_8

The degree of virtuality of an ecosystem could also have consequences for its overall *resilience*, that is, an innovation ecosystem's "ability to adapt to changes in the external environment" (Cobben et al. 2023, p. 5). Resilience has become a prominently discussed capability at various levels of analysis in the context of the global pandemic, including innovation ecosystems (Cobben et al. 2023; Könnölä et al. 2021). Further, digital technologies have been repeatedly discussed as an enabler of resilience (e.g., Xie et al. 2022) which we also ascribe to innovation ecosystems. Adequate degrees of technology dependence, informational value, and temporal dispersion can allow ecosystem actors to anticipate and respond to crises by making use of the right extent, means, and modes of colocated and digital collaboration.

4.3. Boundary Conditions

The emergence of ecosystem virtuality will be subject to boundary conditions (Busse et al. 2017) that influence the generalizability of the relationships we proposed above.

Particularly, we assert that *trust* among actors in an innovation ecosystem will serve as a boundary condition for how ecosystem virtuality can be harnessed toward innovative performance. A collective level of trust has been consistently identified as a key factor in collaborative arrangements such as inter-organizational relationships and virtual teams (Lascaux 2020) as well as innovation ecosystems (Steinbruch et al. 2022). For instance, realizing informational value by choosing appropriate means of collaboration (e.g., e-mail vs. face-to-face meeting) arguably depends on sufficient trust among actors. With regard to the role of trust as a boundary condition for the relationship of digital technology use and innovation, Barrane et al. (2021) conducted a qualitative study of a multi-stakeholder collaboration in new product development and conclude that "innovative organizations must adapt the emergent technologies, new practices and strategies that will support in developing an environment of trust and transparency between the different stakeholders" (Barrane et al. 2021, p. 217). We extend this proposed reciprocal relationship and propose trust to influence how innovation ecosystems can leverage an adequate degree of virtuality for their innovative performance.

Further potential boundary conditions stem from the predominant nature of tasks that are performed in an innovation ecosystem along its evolution (Dedehayir et al. 2018). Accordingly, we deem task characteristics such as type, complexity, interdependence, and required degree of collaboration as likely determinants for the manifestation of ecosystem virtuality.

5. Discussion

In the preceding sections, we have presented a novel conceptualization of ecosystem virtuality, outlined its key dimensions, and proposed potential antecedents, consequences, and boundary conditions. Further on, we discuss the implications of our conceptual framework, suggest potential directions for future research, and conclude with our final remarks.

5.1. Implications

Several theoretical contributions arise from our conceptualization of ecosystem virtuality. Initially, our work calls for a scaled understanding of virtual tool use in innovation ecosystems, and to this aim, bridges the so far distinct literatures on virtuality and ecosystem theory. We thereby respond to calls for a more nuanced consideration of the relationship between digital technologies and innovation eco-systems (e.g., Dąbrowska et al. 2022; Vial 2019). Further, we provide a continuous view between colocated and digital collaboration which has led previous ecosystem research to resort to distinct conceptualizations of digital or regional innovation ecosystems (e.g., Hölzle et al. 2022; Kindermann et al. 2022). Introducing the con-cept of ecosystem virtuality offers a way to capture nowadays convergence of dig-ital technologies and collaboration in ecosystems based on the theoretical premises of socio-material practices (Leonardi 2012). Furthermore, we build upon organi-zational research on virtuality and integrate this in our conceptual framework. Therein, we relate ecosystem virtuality to geographical dispersion as an antecedent, highlight innovative performance as a key consequence, and suggest trust among ecosystem actors as an important boundary condition for these relationships. Hence, we support the translation of established insights from organizational stud-ies on the influence of digital technologies (e.g., Wuersch et al. 2023) to research on innovation ecosystems.

The consideration of virtuality in innovation ecosystems carries various implications for their design, emergence, orchestration, and evaluation. First, designing innovation ecosystems would benefit from anticipating the dimensions of ecosystem virtuality, that is, the reliance on various digital technologies for collaboration as well as the required task- and actor-specific levels of conveyable informational value and temporal dispersion. In practical terms, acknowledging virtuality as an ecosystem property can inform balanced investment decisions for collaboration *infrastructure* such as science and technology parks (Sandoval Hamón et al. 2022) or innovation hubs (Haukipuro et al. 2023). Moreover, setting up innovation ecosystems for adequate degrees of virtuality could broaden their *inclusivity* and better accommodate remote actors from businesses, academia, policy, and society. Second, we argue that businesses engaging in ecosystem-based collaboration should carefully and strategically consider the degree of virtuality and corresponding benefits and pitfalls in the respective emerging innovation ecosystem (Budden/Murray 2022). Here, more digital collaboration with a broader pool of potential actors can strongly impact key business activities through more diversified knowledge sharing, greater international reach, and in turn, novel innovation opportunities. Third, the orchestration and governance of innovation ecosystems correspond closely with their digitally-enabled formal and informal structures and processes. For instance, insight into the manifestation of virtuality can aid ecosystem orchestrators in developing the resilience of an innovation ecosystem (Könnölä et al. 2021). Fourth, and lastly, assessing degrees of virtuality *across* innovation ecosystems can prove as a valuable criterion for *evaluative instruments* in policy-making, and eventually, inform decisions to enhance digital infrastructures (Lynn et al. 2022).

5.2. Future Directions

In light of our conceptualization of ecosystem virtuality and its implications, promising avenues for future research come into consideration regarding ecosystem theories, operationalizations, and the incorporation of advancing digital technologies.

While the scope of our article is geared toward innovation ecosystems, the notion of virtuality could also be employed for related ecosystem concepts. For instance, Wurth et al. have recently noted "a shift in the importance of geographical proximity (e.g., working from home, remote working, digital economy)" (Wurth et al., 2022, p. 758) for *entrepreneurial ecosystems*, calling for future research to address this observation. A virtuality perspective could help to further differentiate and specify the role of digitalization for entrepreneurial ecosystems (see also Zahra et al. 2023).

This article provides the conceptual grounds for operationalizing virtuality as a property of innovation ecosystems. Future empirical works could involve the internal and external validation of the construct and its underlying dimensions through qualitative and quantitative means. Further, our conceptual framework of ecosystem virtuality offers initial relationships that could be tested in case designs or correlational studies. An interesting question would be whether virtuality is best assessed as a composite of objective measures or could also involve *perceptions* of virtuality (similar to a recent perspective in teams research put forth by Handke et al. 2021).

Finally, the recent advent of user-friendly interfaces for generative artificial intelligence (AI) has put emphasis on the transformative role of AI not just for individual knowledge work, but also for collaborative innovation (e.g., Brem et al. 2023). This poses the question of how AI will be integrated with innovation ecosystem structures and processes, and eventually, how this phenomenon corresponds with ecosystem virtuality. A further prominently debated technology concerns the evolution of collaborative XR environments (e.g., digital twins) toward instances of the so-called 'industrial metaverse' (Li et al. 2023). While connected metaverse instances can be viewed as an ecosystem in itself (Schöbel/Leimeister 2023), the emergence of such boundary-spanning instances could also involve their relationship with established innovation ecosystems. XR-enabled metaverse instances could score very differently across the dimensions of ecosystem virtuality, especially regarding their informational value, i.e., the richness and adequacy of the conveyed information. Hence, an important boundary condition worth exploring lies in the task-specificity of industrial metaverse instances. Applying the ecosystem virtuality lens would allow for a balanced approach to integrating industrial metaverse instances in innovation ecosystems.

5.3. Conclusion

Collaboration in present-day innovation ecosystems is neither purely digital nor always colocated but instead exists on a nuanced spectrum. To shed light on this phenomenon, we introduce the concept of ecosystem virtuality, a novel property of innovation ecosystems. Our article bridges established insights from organizational and ecosystem research as we translate virtuality to the ecosystem level and outline its theoretical premises and underlying dimensions. Further, we integrate ecosystem virtuality in a conceptual framework and highlight potential antecedents, consequences, and boundary conditions. Our conceptualization of ecosystem virtuality helps ecosystem actors navigate the intricate interplay of digital and colocated collaboration in innovation ecosystems and provides a way ahead for empirical validation.

DOI: https://doi.org/10.30844/wgab_2023_8

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Increasing Resilience in Factories: The Example of Disturbance Management – A Research Approach

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Disruptions in in-plant production systems, such as variant-rich series production, can lead to serious production downtimes. The longer the production stoppage lasts, the greater the damage to companies and supply chains. The capabilities to ensure emergency operation until full performance is restored after disruptions as well as the fast restart of production systems represent a crucial competitive factor for companies and also increase production agility. Therefore, it is of central importance to reduce the time between the occurrence of a disruption and the return to the initial level in order to minimize downtime costs.

In the context of this paper the state of research on disturbance management and assistance systems for disturbance management ist stated and a research approach for investigating the potentials of assistance systems will be presented.

1. Initial situation

The term *resilience* is used to describe capabilities and skills that enable a return to the original state after a disruption. Resilience is quantified as the time between the occurrence of the disruption and the return to the initial level, based on the system performance, as in (Zobel/Khansa 2014). In this context, resilience can refer to the system, the human or the organization, which must be considered as factors of the entire production system (Bläsing/Bornewasser 2021). Due to an increasing individualization, flexibilization and complexity of production, there are always new demands on the employees (Wolf et al. 2018, Gronau et al. 2017), such as the elimination of new, diverse disturbances. In order to resolve the disruptions quickly, humans can be supported, for example, by additional information, data, or instructions in the form of handling instructions for decision-making and disruption resolution. This contributes to a reduction in disruption times, which increases the resilience of the entire production system.

DOI: https://doi.org/10.30844/wgab_2023_9

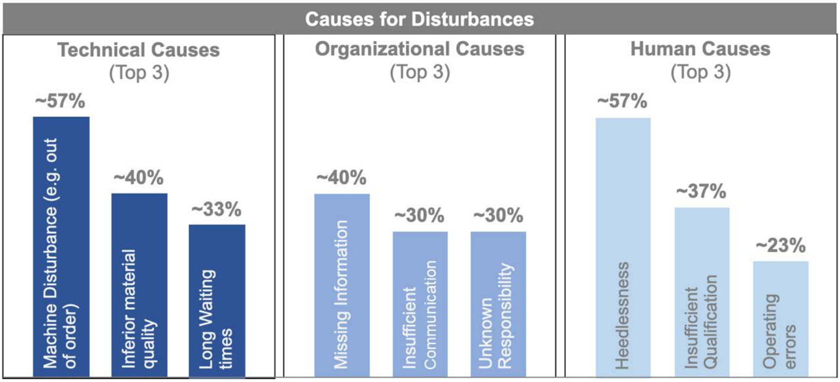

Figure 1: Causes for Disturbances (Gronau et al. 2019)

The action patterns for fault elimination can be presented to the human with assistance systems to support a quick elimination of the fault. In addition to short-term support, process-oriented, problem-based knowledge transfer with assistance systems should be used in the medium and long term to promote the development of employees' technical skills and enable work-integrated learning (Burggräf et al. 2021, Dostert/Müller 2021). To date, the possibilities for further training through assistance systems have hardly been investigated and used (Burggräf et al. 2021). The described potential can only be exploited if the selection and design of the assistance system are target-oriented in relation to the target group (Mark et al. 2020, Traub et al. 2018], area of application (Mark et al. 2021) and disruption. In order to develop expertise, understood as the transfer and application of action patterns to various disturbances, a classification and evaluation of disturbances must first be made possible depending on individual company characteristics. The identified disturbances must then be assigned to the appropriate action patterns.

2. State of research

2.1. Disruption Management

In production, disruptions are understood as unexpected temporary events whose occurrence and frequency cannot be predicted (Galaske/Anderl 2016, Stricker/Lanza 2014) and which prevent further work. An extended concept of disturbances sums up everything that prevents the factory from working optimally (Hingst et al. 2023). Disturbance variables can be subdivided into categories such as human, machine, material, management, measurability, environment, and method, among others (Meyer et al. 2013). Efficient disruption management is an important foundation for successful business operations (Burggräf et al. 2017).

The elimination of disturbances can be divided into preventive and reactive measures (Stich et al. 2017). A distinction is made between combating the causes and containing the effects (Schröder et al. 2016).

An operational task of reactive fault management is the elimination of the above-mentioned faults (Spath/Braun 2021). The process of disruption management includes four steps: Detecting the disturbance or disturbance effect, finding the disturbance cause, developing an appropriate response, and eliminating the disturbance cause (Bauer et al. 2014, Galaske/Anderl 2016). The time from the occurrence of the disturbance to the end of the disturbance effect can be divided into a latent and a manifest phase (Stricker/Lanza 2014). In the latent phase, the disturbance already occurs, but its elimination does not begin until the manifest phase starts.

In order to perform the fault elimination more efficiently and economically, manufacturing execution systems (Hingst et al. 2023) are used and approaches of manufacturing analytics are tested to be able to detect faults from the multitude of data provided by sensors (Denkena et al. 2020, Jordan et al. 2015). Finally, expert systems were built to increase efficiency and troubleshoot faults (Iwanek et al. 2015). The knowledge management approach has been adopted to increase the resilience of production through knowledge transfer (Hingst et al. 2021). Institutional learning is also rarely incorporated in the field of disruption management (Pantazopoulos 2013).

In principle, holistic disruption management also includes avoiding disruptions through appropriate preventive measures (Foon/Terziovksi 2014; Fraser et al. 2015). This contribution concentrates only on the so-called Breakdown Corrective Maintenance.

Simulation as a method for mapping production processes and for investigating effects that cannot be investigated to the same extent in reality is widely used in engineering (Riley 2013; Trigueiro de Sousa Junior et al. 2019]. In the environment of disruption management, among others, (Galaske/Anderl 2016) use simulation to test resilience strategies, (Trigueiro de Sousa Junior et al. 2019) to increase transparency in case of disruptions in global production networks (Burggräf et al. 2018) or to determine the advantageousness of preventive measures to avert disruptions. Simulation is also widely used to study supply chain disruptions (Ivanov/Sokolov 2013).

Enterprise resilience can be considered statically as a result of preparedness and preventive actions, or dynamically when disruptions can be handled appropriately and the previous state can be quickly restored (Annarelli/Nonino 2016). However,

DOI: https://doi.org/10.30844/wgab_2023_9

reactive measures must not be neglected to achieve the highest possible resilience, since disruptions cannot be avoided entirely. While the robustness of a production system is described by its ability to react to changes (Hingts et al. 2021), resilience additionally considers dynamic components in dealing with disturbances (Stricker/Lanza 2014). Accordingly, resilience is defined, among other things, by how quickly a production system can restore its original state as a result of a disruption (Tierney/Bruneau 2007). The role of the employee is a central component in this context, since the employee is directly involved in the elimination of the disturbance. Due to a large number of possible forms of disturbances (Stricker/Lanza 2014), the individual consideration of possible disturbances or disturbance patterns is particularly relevant.

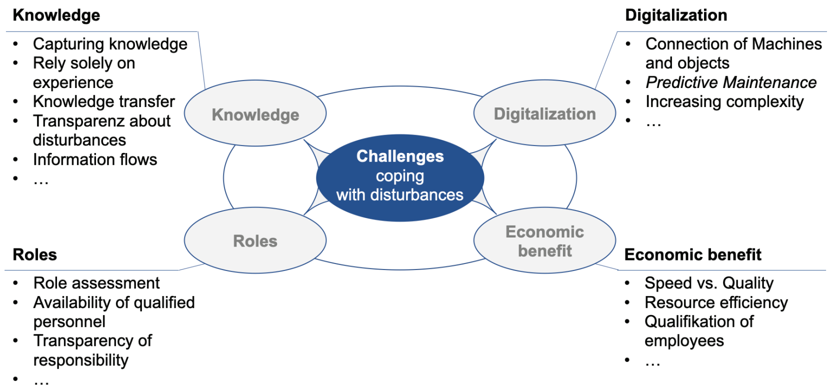

Figure 2: Challenges coping with disturbances (Gronau et al. 2019)

The authors conducted a questionnaire survey on the current state of disruption management as well as the identification of challenges in dealing with production disruptions (Gronau et al. 2019). The results of the survey illustrate the relevance of disruption management, but also show that disruption management is still at an early stage in many companies despite many years of studying this topic. The reasons for this include problems in dealing with empirical knowledge and a lack of information and transparency. The study also revealed that, in addition to obvious technical causes of disruptions, organizational and human causes also frequently lead to disruptions in production systems. In this regard, employee carelessness can be cited as one of the most common causes (Gronau et al. 2019).

2.2. Demand-oriented competence development through assistance systems in production or disruption management

Assistance systems are used in a variety of ways. In the literature, assistance systems are divided into sensory (e.g., haptic glove, arm support, smart watch), physical (e.g., robots, AR and VR applications), and cognitive (e.g., computer assisted instruction, voice control, AI-based intelligent personal assistant) assistance systems (Mark 2021). In the proposed research project, the use and design of assistance systems in the context of production and industry will be investigated. There, work environments are characterized by increasing complexity, flexibilization and individualization (Kagermann 2014), which is why assistance systems are used to support humans (Bläsing/Bornewasser 2021). By providing additional information (e.g., instructions) and data, assistance systems can support decision-making and troubleshooting and, provided they are designed correctly and used appropriately, minimize the cognitive workload (Bläsing/Bornewasser 2021).

In automated production environments, such as variant-rich series production, humans increasingly take on complex tasks that, in combination with performance monitoring, can lead to increased stress among employees (Kaasinen et al. 2020). In particular, when a malfunction occurs, he or she has to overview complex situations and diverse data in a short time, make decisions, and carry out the troubleshooting. For this purpose, data from various sources must be integrated and interpreted. Assistance systems support humans, for example, by bundling information from various data sources and enabling decision and action recommendations. For example, data glasses can be used to provide employees with additional information while leaving both hands free to perform tasks (Danielsson 2020). In this way, employees, as active agents in the troubleshooting process, are supported, which helps to resolve the malfunction faster and thus increases the resilience of the production system.

Various types of assistance systems and (potential) technical implementations are described in the literature, but only some of them are used in industry. It is clear, however, that there is a lack of scientific foundation for target group and context-specific selection and design of assistance systems as well as experimental validation of their effectiveness (Mark et al. 2021). (Burggräf et al. 2018) also describes the potential and necessity of an individual and adaptive design of assistance systems, which is adapted to the target group, field of activity and company specifics. Particularly in the event of a malfunction, which causes great time pressure, assistance systems can only have a supporting effect if they are adequately selected and designed and recommend suitable instructions for action for the malfunction in

DOI: https://doi.org/10.30844/wgab_2023_9

question. This is the starting point of the present application. First, a systematization of disturbances and the derivation of action patterns for the specific selection of assistance systems will be developed and then the effectiveness will be investigated experimentally.

In addition to short-term effects in the use of assistance systems on rapid fault elimination and increasing the resilience of production systems, medium- and long-term effects on the competence development of employees are pursued in this application. The assistance system-supported troubleshooting promotes the technical competence of the employees, so that a transfer of specific action patterns to further disturbances is made possible. The universal application of learned action patterns reduces the time required for troubleshooting and thus increases the resilience of the entire production system.

The visual, auditory, or haptic provision of information, data, and action instructions is directly linked to the motor execution of the troubleshooting process in the event of a malfunction and is confirmed by feedback as a success or failure in troubleshooting. A transfer to other malfunction classes enables the embedding of the conveyed information and action instructions by the assistance system in the overall context. The addressed development of expertise is necessary to counteract the effect of the "Ironies of Automation". The effect was already described in 1983 and has been unsuccessfully attempted to address since then, which is why it is still highly topical. The effect describes the fact that in the context of industrial production environments, humans increasingly find themselves in the role of supervisors. Thus, he takes over fewer operational activities, but must, for example, carry out the rectification in the event of a malfunction. On the one hand, increasing automation causes a loss of situational awareness and skills of humans, since they act less actively (Strauch 2018; Bainbridge 1983). At the same time, however, the high complexity of fault recovery requires detailed knowledge and knowledge of the context and overall process in order to resolve the specific fault case (Bainbridge 1983). Current training structures such as off-the-job training, training courses, e-learning or one-time on-the-job briefings are not sufficient to impart this specific and problem-based technical and contextual knowledge so that knowledge and action patterns can be adapted and applied to different situations. This prevents a sustainable transfer of what has been learned to the workplace (Rangratz/Pareto 2021). The assistance systems present the employee with problem-based information and data in the event of a malfunction. By embedding the information in a context-specific manner and linking it to action patterns, process-oriented learning of technical competence is to be promoted Cooper et al. 2010). Competencies are skills and knowledge to cope with a specific problem in a practical way. Competencies are divided into different facets (Oberländer et al. 2020), whereas in this contribution the technical competence is addressed. By means of an assistance system-supported troubleshooting, the development of technical competencies has to be promoted and thus the transfer problem of formal, external further training has to be addressed.

3. Derivation of the research gap

Based on the described state of research in incident management, the essential goal of research in this area has to be to investigate the current situation of incident management in companies, to identify suitable characteristics and action patterns and to transfer them to incident management. The achievable benefit is investigated using a simulation and in practice through the situation-optimized selection of assistance systems. Following this research path it is possible to extend the theory of management science on reactive fault elimination by innovative aspects using the example of variant-rich series production. For this purpose, it fits into a simulation-based research framework that is spanned by approaches such as (Mason et al. 2005) (mapping human performance) and (Barad 2001) (improvement models for manufacturing strategies).

So far, no approach exists which links disturbance classes, action patterns and assistance systems. Therefore, no artifact exists that helps companies identify these connections and use them to increase resilience. In addition, companies face the problem of continuously training employees in a practical manner so that a transfer of what they have learned to work problems is ensured. Therefore the following research questions arise:

F1): How can specific action patterns be derived and generalized for application in production for the employee in relation to the disturbance classes of a production?

F2): How can assistance systems be assigned to the different action patterns according to need for optimal elimination of the disruption and increase of the resilience of the production system?

F3): What are the effects of assistance system-supported fault elimination on employees' long-term competence development?

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4. Research proposal

To answer the research questions, an improved design of assistance systems in different production scenarios is necessary. It has to be be enabled on a technical-conceptual level based on a generic fault classification framework. An experimental study may provide insights into the effectiveness of competence development measures for specific disruption patterns.

4.1. Objectives

Essentially, the following four objectives have to be fulfilled in order to reduce fault rectification times, to sustainably qualify the worker to rectify the fault and to minimize the consequences of the disturbance for the company:

- Identification of malfunction classes for the development of a classification framework, which enables a malfunction classification in the production

- Determination of a solution-oriented classification of the specific action patterns, which are suitable for the disruption management, in a classification framework

- Derivation of a procedure for fault elimination with the help of a demand-oriented selection of the considered assistance systems to increase the resilience of the production system

- Based on the findings, expand existing innovative approaches to incident management and formulate implications for incident management to accelerate the selection and deployment of assistance systems, thereby enhancing the expertise of employees, enabling the transfer of learned patterns of action across different incidents

4.2. Procedure

On the one hand, the knowledge gained from the disturbance classification framework should enable further development or redesign of the integration of assistance systems for disturbance elimination, and on the other hand, it should also produce new procedures or methods for disturbance elimination. A key objective must be to investigate the effectiveness of the assistance system-supported troubleshooting on the development of the professional competence of the employees and thus to achieve an increase in the resilience of the production system.

Accordingly, the proposed research design is a combination of desk research (literature review, conceptual work), case studies, simulation, and expert interviews and uses both qualitative and quantitative research methods.

Based on the knowledge gained from the literature on disruption management, exploratory case studies will be conducted to provide insight into the practical design of disruption management and thus empirically gained input.

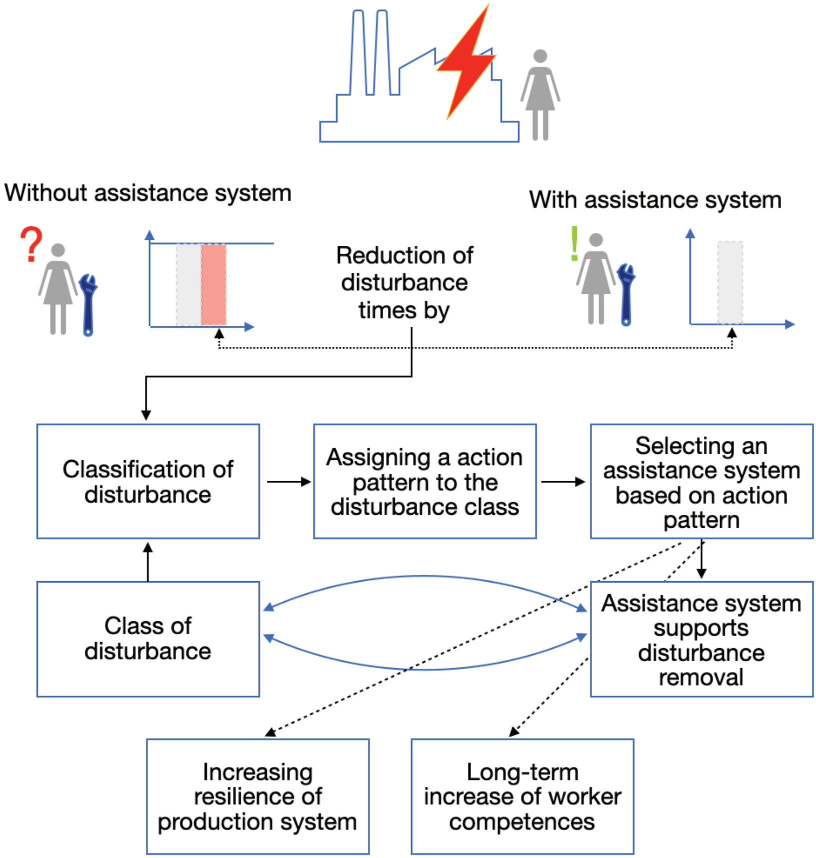

Figure 3: Proposed research design

It makes sense to develop a generally valid approach for the classification of disturbances and for simplified assistance system selection. Through an experimental study, the effectiveness of assistance system-supported disturbance elimination on the resilience of the production system and on the development of the expertise of the employees can be tested through a targeted selection and use of different assistance systems in order to derive a recommended course of action that is valid for individual company situations. This holistic method can then later be validated in industrial practice using various case studies.

DOI: https://doi.org/10.30844/wgab_2023_9

4.3. Expected Results

As a result of the research project, a basis for linking disturbances, forms of production, measures for disturbance elimination and assistance systems for the analysis and elimination of disturbances by employees is to be developed.

Identified disturbance clusters and their interaction on the production system will be supplemented by possibilities of a transfer of specific action patterns between disturbance clusters. This will enable an assessment of effectiveness and transfer possibilities in the context of disruption management.

A further result of the research should be a generally valid model which, in addition to the formation of individual clusters, enables the selection and formation of suitable action patterns. This includes an account of the effectiveness of the possible action patterns for individually occurring disturbances.

If a broad data base exists on disturbance resolution supported by an assistance system, this can be used to validate the disturbance classification scheme.

Overall, resilient fault elimination is achieved with the help of a learning-friendly design of the assistance systems.

5. Outlook and further work

The paper has shown that there is a research opportunity for the use of assistance systems in disturbance management. Further research, together with industrial partners has yet to show how these assistance systems could be constructed and implemented and how much influence they have on aspects like earlier recognition of disturbances, earlier definition of the necessary measures and less costly disturbance management over all.

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Green Digital Twins in the Product Life Cycle

Opportunities and Challenges for Sustainability Engineering

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Mikhail Polikarpov, René Wöstmann, Florian Hoffmann

1. Introduction and Motivation

Reducing emissions from industrial processes is a critical step toward achieving global climate protection goals since this sector is a major contributor to global emissions (ClimateWatch 2023). As a result, several countries worldwide set aspirational targets. For instance, Germany has set a goal of reducing its emissions from industrial production by at least 20% before 2030 (BMWK 2021). In order to achieve these objectives, innovative technologies are required that pave the way for sustainable industrial production systems.

Digital technologies offer new opportunities to analyze energy and resource consumption and derive data-driven improvements that contribute to climate protection. The demand for traceability solutions up to the product carbon footprint and digital product passports has increased since the establishment of EU regulations (Europäische Union 2019, 2020), and digital technologies have emerged as a powerful enabler to meet this demand (Europäische Union 2019). The potential benefits of green Digital Twins offer a technological solution for a sustainable transformation. The term 'green' refers to sustainable and environmentally friendly practices and attributes designed to optimize energy efficiency, minimize carbon emissions and reduce the environmental impact of physical systems. These include particularly its ability to provide traceability and reduce climate-damaging emissions by up to 8% and energy consumption by 20% (accenture 2021). Various industries use digital twins to optimize processes, predict failures and facilitate decision-making (Barthelmey 2021; Barthelmey et al. 2019). Standardization and demonstration activities such as the Asset Administration Shell (Bader et al. 2022), the Digital Factory Framework (IEC 62832 2020), and the Equipment Behaviour Catalogues (ISO 16400 2020) help significantly to establish the digital twin as a tool in the industrial environment. However, existing approaches do not yet consider sustainability and its environmental impact throughout the product life cycle.

DOI: https://doi.org/10.30844/wgab_2023_10

The product design establishes the basis for sustainability throughout the product life cycle. Sustainable material choices based on environmental impact and recycled or biodegradable materials can reduce the product's impact. Optimizing energy efficiency and resource consumption during the design stage is possible by simulating different scenarios. Furthermore, designing products with a circular approach supports reusing or recycling at the end-of-life. Digital twins can also evaluate end-of-life scenarios to optimize sustainability. By considering sustainability during the design stage, products can be innovative and environmentally responsible.

Today's production planning phase focuses on optimizing the trade-offs between cost, quality, and time. Industry 4.0 and its technologies offer opportunities to improve production planning holistically, including sustainability aspects. In order to find not only the most efficient but also the most environmentally friendly solution, aspects such as carbon dioxide equivalents (CO_2e) must be taken into account in production planning with tools such as simulation and forecasting.

Digital twins provide transparency into the production process by establishing data structures focusing on sustainability, real-time energy consumption, resource use, and carbon emissions. This information enables producers to identify areas for improvement and implement strategies to reduce environmental impact. By using the digital product twin to assess the sustainability information of (semi-finished) products in the production process, such as raw materials and packaging materials, producers obtain the ability to make informed decisions.

The end-of-life (EOL) management of products plays a significant role in environmental protection, which involves the implicit target of safe waste disposal. However, existing products on the market pose a particular challenge due to missing component composition and emission transparency. A representative example is refrigerating appliances, which commonly contain halogenated chlorofluorocarbons (CFCs). Approximately 1.5 million used refrigerators are estimated to contain fully or partially halogenated CFCs in Germany, with a total climate potential of roughly 4 million tonnes of CO_2 equivalents (Deutsche Umwelthilfe 2016). Therefore, the development of green Digital Twins for the end-of-life cycle could provide efficient and input-adapted control for the recycling process. Existing approaches have yet to create green Digital Twins of EOL products to predict the presence of climate-damaging components such as refrigerants.

This research paper explores how green Digital Twins lead to sustainable industrial production along the product life cycle. The research findings contribute to achieving climate protection targets by presenting opportunities and challenges to reveal emissions and construct green Digital Twins for different purposes.

2. Integration concepts and techniques

Digital Twins have emerged as a powerful tool for simulating, analyzing, and optimizing physical assets, systems, and processes across various industries. They are considered the highest level of digitization of physical assets (see Figure 1). Digital Models represent the baseline, which provides a reliable and accurate representation of their physical counterparts. However, integrating data from physical entities into digital models is typically done manually. Digital Shadows are characterized by the automated, unidirectional data flow from the physical to the digital object. Digital Shadows are widely used in the manufacturing industry to monitor and analyze the performance of machines and equipment in real-time. Automated information flow from the digital to the physical entity and vice versa defines Digital Twins. These can provide recommendations to the user and intervene in production planning and control to find optimal operating points.

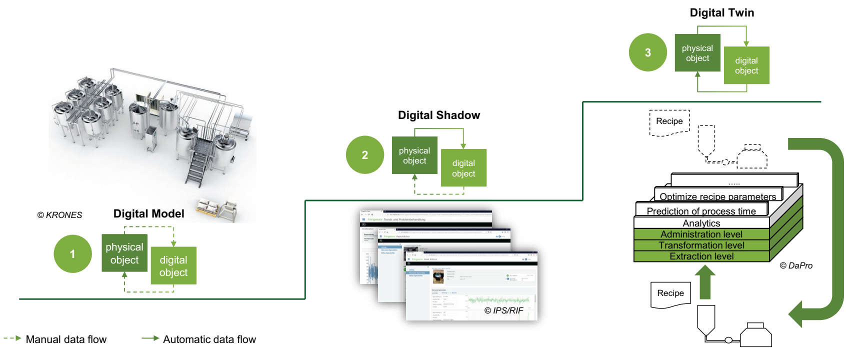

Figure 1: The distinction between digital model, digital shadow and digital twin (Kritzinger et al. 2018; Wöstmann et al. 2022)

The Asset Administration Shell (AAS) is a standardized information model developed by the platform Industry 4.0 describing the characteristics and behavior of an industrial asset, providing a way to represent and exchange information about assets, enabling interoperability and integration across different systems and organizations. In the AAS, submodels are logical components that represent specific aspects of an asset, such as its structure, behavior, or capabilities. One example is the carbon footprint submodel which enables sharing and retrieving of relevant information per product throughout the supply chain while considering the existing standards. This will enable interoperability and transparency regarding carbon footprint information. (Platform Industie 4.0 2022)

The integration of existing industrial plants into the Internet of Things (IoT) and Services offers many opportunities and poses challenges for many users. IoT lends itself to the merging of internal machine data, external sensors, and adjacent system landscapes.

In the IoT area, numerous cloud solutions offer suitable options for performing both data storage and data aggregation, thus creating with DT an essential basis for data analysis.

IoT and AAS submodels have initial applications in the field of sustainability, but the spread of holistic methods and systems is yet to be established.

3. Sustainable integration concepts

Over the past few decades, there has been an emerging awareness of sustainability as a crucial factor in industrial practices. With increasing concerns over the impact of anthrophonic climate change (Weart 2008), industries worldwide are beginning to recognize the importance of adopting sustainable practices, as producing products inherently generates CO_2 emissions through value-adding processes and associated logistics. As a response, many companies and research institutions are seeking solutions for sustainable integration concepts.

In the face of the pressing need to reduce greenhouse gas (GHG) emissions globally, principles for their objective assessment were established in the ISO 14060 series of greenhouse gas standards (Blue Carbon Projects 2023). In this context, the DIN EN ISO 14064-1:2019-06 (DIN EN ISO 14064-1 2019) defines the essential fundamentals for quantitatively determining Carbon Dioxide equivalent (CO_2e) emissions for organizations. The GHG protocols have been established as widely recognized international accounting tools to further aid in measuring, managing, and reporting GHG emissions. These protocols distinguish between three scopes of emissions: direct GHG emissions (Scope 1), indirect GHG emissions from energy consumption (Scope 2), and all other indirect GHG emissions (Scope 3). Moreover, the DIN EN ISO 14064-2:2020-05 (DIN EN ISO 14064-2 2020) expands upon the principles of CO_2e emissions balancing with procedures for quantifying, monitoring, and reporting emission reductions. Furthermore, the DIN EN ISO 14064-3:2020-05 (DIN EN ISO 14064-3 2020) provides guidelines for those who verify and validate greenhouse gas data and information.

The Life Cycle Assessment (LCA) method, as standardized by ISO 14040:2006 (ISO 14040 2006) and ISO 14044:2006 (ISO 14044 2006), is the dominant approach for evaluating the environmental impact of products. This method considers the entire product life cycle, enabling the calculation of the ecological impact of a product through a standardized procedure. LCA can also be used to analyze subprocesses of the life cycle, such as production, through Simplified Life Cycle Assessment (SLCA) studies. However, LCA is a static method based on statistical data, and dynamic aspects of production can greatly influence production processes. Therefore, the Discrete Event Simulation (DES) method has been combined with LCA in DES-LCA to include dynamic aspects of production in LCA analysis. Overall, LCA provides a comprehensive understanding of the environmental impact of a product or service, including its contribution to climate change, air and water pollution, land use, and resource depletion, which can help identify opportunities for improvement in the production process, use, and disposal stages. (Deuse et al. 2022)

Sustainable integration concepts are at the forefront of Industry 4.0, leveraging advanced technologies to create a more sustainable and responsible future for the industrial sector. A key idea in this regard is the green Digital Twin, which combines the emerging trends of digitization of physical systems and sustainability efforts. Green Digital Twins can identify inefficiencies and optimization opportunities by providing real-time information on energy usage, carbon emissions, and other environmental metrics. It aims to reduce energy consumption and emissions, promote environmentally friendly practices and improve the properties of physical systems. Green Digital Twins are a promising technological solution for achieving sustainable transformation in the industrial sector and have the potential to play a crucial role in shaping a more sustainable future.

4. Conception of a green Digital Twin in the product life cycle

The green Digital Twin is based on an information model that focuses on sustainability aspects at each stage of the product life cycle. It enables the optimization of processes, products, and resources in terms of material use, waste, and greenhouse gas emissions throughout the life cycle. Early decisions have a major impact on the later stages of the product life cycle, shaping product and process design and setting the boundaries for subsequent production, usage and end-of-life cycle. Later stages rely on the strategic planning established in earlier stages. The green Digital Twin extracts, transforms, and loads selected information for sustainable applications. Each stage of the product life cycle requires different information regarding sustainability aspects. Relevant emission information is created by generating electric energy, process heat, physical processes, chemical processes, transportation, and fugitive emissions. To create a holistic model, each stage must define climate-damaging processes and the data behind them. In the context of climate protection, linking product development, process development, production, usage, and end-of-life through the green Digital Twin can significantly impact the product's carbon footprint. The interconnectivity enables a data-based LCA.

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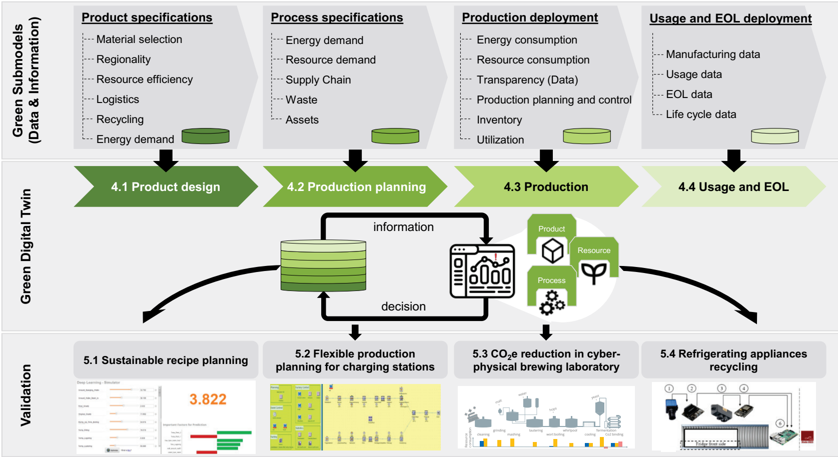

Figure 2: Proposed framework of a green Digital Twin in the product life cycle

4.1. Product design

The product design stage has a crucial role in determining the resource allocated to a product, thus impacting production planning, production, usage, and EOL considerations. Key aspects influencing the carbon footprint include material selection, regional and international impacts, use of renewable energy, resource efficiency, energy consumption, packaging, and transportation. The integration of simultaneous engineering and agile planning methods into product design allows the product lifecycle to be directly considered, enabling flexible adaptation towards green product design. It is therefore essential that recycling aspects such as disassembly, recyclability, disposability, remanufacturability and reusability are taken into account during product design. By incorporating these factors, sustainable practices can be integrated into the product design process, ensuring resource efficiency, environmental responsibility, and circular economy principles.

4.2. Production planning

Modern approaches to production planning focus on parallel work rather than just the sequential process. However, the data of classical and modern planning methods and their decisions must be evaluated for their sustainability. The sustainable information must be considered by existing approaches such as agile product development planning, simultaneous engineering, and classical planning approaches.

Existing approaches, such as ISO 18828 (ISO 18828 2018), describe a framework for production planning. It includes a reference planning process, descriptions of information flows between each discipline (manufacturing, assembly, logistics, and layout), key performance indicators in the planning process, and impulses for data-driven manufacturing change management. Existing standards need to be expanded to include an ecological production planning perspective. Technological approaches in engineering can lead to significant energy savings, such as the use of direct drives, optimization of power transmission, standby measures, dual production, and avoidance of over-engineering. Integrating technologies in the early stage of the production planning process brings immense potential to minimize energy and resource consumption (Braun et al. 2010; Herrmann/Thiede 2009; Hülsemeyer 2016; Thiede 2012). Novel approaches consider the future energy requirements of a process chain during its planning stage (Schrems et al. 2011). This allows for a comparison of various manufacturing processes based on their energy usage and the anticipation of the overall energy demand of the forecasted process chain. Also, the reflection of energy consumption in specific operating states of the production equipment can create insights into the process chains' energy consumption (Weinert et al. 2011). Another approach is to compare the energy demand of each process step and materials to determine energy-intense processes which may be relocated. An energy-efficient production planning can be achieved by considering factors such as process technology, batch size, scheduling, and peak load reduction (Abele et al. 2020; Bank et al. 2021; Biel/Glock 2016; Liang et al. 2019; Mousavi et al. 2016). Scientific approaches for integrating ecological factors in process chain planning include forecasting energy and resource consumption. Process knowledge is generated through data collection and analysis while facilitated by digitization and process models. Both methods are based on historical, real-time, or simulation data, which needs to be aggregated in the corresponding submodel of the green Digital Twin. By integrating green Digital Twins of the production process, it is possible to predict output variables, such as energy demand, based on the input variables and process parameters. At the process design stage, process parameters can be selected to reduce energy consumption. Inputs include raw materials, supplies, and energy, while outputs can be products, semi-finished products and/or waste. Simulations, Cloud Technology, and IoT can also be used to test different production scenarios to create a flexible production planning that meets the customer's demand, and no unnecessary resources are planned (Carvalho et al. 2020). Intralogistic concepts are reducing the energy consumption of cyber-physical fleets due to data-driven fleet management and vehicle routing (Wang/Wang 2019).

Flexible production systems are important in terms of economic efficiency and resource consumption. Oversizing a system can lead to additional environmental impacts even before implementation due to the production of additional machines, systems, and conveyors that are not needed in later production operations. During production, too large production capacities result in additional resource consumption, which has a negative impact on the product's carbon footprint.

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For this reason, the choice of a simultaneous planning approach consisting of product design and production planning is essential when planning future production capacities. Since individual market environments exhibit a certain degree of volatility, system-immanent flexibility must be considered in a simultaneous planning approach. It makes it possible to react to market changes despite basic capacity planning and thus reduces the waste of resources. Production system flexibility can be achieved, for example, by integrating partial automation technologies (e.g. human-robot interaction). Human-robot interaction enables the division of labor between humans and robots, which allows planning configurations to be made depending on the number of units. (Hoffmann et al. 2022)

Such planning approaches are highly complex and require suitable planning tools and methods, such as the discrete-event material flow simulation (VDI 3633 2014). It enables the simulation of different line, organization, and number-of-units configurations for mapping within a digital image of the later system. Thus, the implementation within a green Digital Twin is also possible, making the simulation results available for other life stages.

4.3. Production

Throughout the production stage, the previously developed sustainability-conscious measures are implemented. This takes effect in the framework of sustainable manufacturing through the consortium of intelligent manufacturing equipment, systems, and services (He/Bai 2021). Approaches to drive sustainability during manufacturing incorporate aspects ranging from sustainable manufacturing technology, workstations and manufacturing system, standard measures, value stream audits for evaluating sustainability performance, and lean manufacturing practices to real-time monitoring and control of the whole supply chain (Hariyani/Mishra 2022). A key enabler in the context of sustainability is Industry 4.0 and its technologies (Blunck/Werthmann 2017; Enyoghasi/Badurdeen 2021), providing important environmental, economic, and social prosperity (Sartal et al. 2020).

The submodel of a green Digital Twin for production entails key factors and indicators of sustainability, including transportation, energy consumption, and processed materials considering the three emission scopes of the GHG protocols (ISO 14040). It is crucial to guarantee a certain level of transparency during production to provide monitoring capabilities of the actual process. This allows the identification of discrepancies between planned and occurring emissions as well as the detection of potential bottlenecks in production processes. Such transparency is achieved through Big Data uncovering actual resource and energy consumption as well as resulting environmental impact. Furthermore, appropriate optimization and simulation achieve increased reliability of demand planning and overproduction, optimal manufacturing component utilization, increased resource consumption efficiency, and improved inventory management (Enyoghasi/Badurdeen

2021). During operation, Industrial Internet of Things (IIoT) provides insights into the production and helps in enhanced decision-making toward sustainability-aware directions. Finally, a green Digital Twin-driven production system assists through industry 4.0 technologies in the efficient setup of machines that require calibration beforehand by reducing the amount of produced defective goods and associated material costs.

In case sustainability awareness arises during or after the production stage within the product life cycle, it is difficult to draw conclusions on the sustainability impacts of planning decisions. A retrospective analysis of existing product design and production planning decisions is essential to generate future transparency and improvement regarding the sustainability of developed products.

4.4. Usage and EOL

According to the "Proposal for the new Ecodesign for Sustainable Products Regulation" (ESPR) of the European Commission (European Commission 2022), Digital Product Passports (DPP) contain information about a product's composition, the origin of the components and should also provide data necessary to assess the environmental and societal impacts during production, usage and transformation stages of the product life cycle. Jansen et al. (Jansen et al. 2023) distinguish between the DPP itself and the supporting DPP system, which is the underlying software system that facilitates interactions between various stakeholders along a product's life cycle to consolidate required information. General DPP system and software quality requirements incorporate aspects in regard to legal obligations, functional suitability, security, confidentiality, IP protection, interoperability, modularity and modifiability, accessibility, availability and time behavior (Jansen et al. 2023).

Requirements for a DPP were alternatively subdivided by (Plociennik et al. 2022) into information, collaboration, identification, and legal requirements. Especially interesting in the context of the current paper is the classification of required data into:

- Manufacturing data (product composition, materials, component weights, details about the manufacturing process, physical and chemical properties of materials, hazard class)
- Usage data (documentation of changes in a complex product, e.g. documentation of part replacement or repair)
- EOL data (documentation on collection, sorting and treatment, applied recycling method, recording of achieved collection fraction)
- Life cycle data (sales volume, guidelines for storage and usage, purchasing decision aid based on environmental and societal criteria)

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5. Use cases of green Digital Twins in the product life cycle

The following four use cases describe representative green Digital Twins for the product life cycle stages. These include sustainable recipe planning, flexible production planning for charging stations, CO_2 reduction in a cyber-physical brewing lab and refrigerating appliances recycling. Utilizing real-time data, machine learning models and simulation, these green Digital Twins showcase informed decision-making, optimized resource consumption, and reduced environmental impact throughout the product life cycle.

5.1. Sustainable recipe planning

A first approach of proactively predicting CO_2 emissions and optimizing products and processes can be demonstrated within a cyber-physical brewing laboratory at the RIF Research Institute for Research and Transfer e.V. (RIF) in Dortmund and at the Centre for Advanced Manufacturing University of Technology Sydney (CAM UTS) in Sydney with the goal of ML-based recipe planning. By enhancing the physical brewing assets towards green Digital Twins regarding CO_2 emissions as well as material and energy consumption, machine learning models are developed to predict and optimize CO_2 emissions. Key sources of CO_2 emissions include fermentation (Scope 1), energy consumption for heating and cooling (Scope 2) as well as raw material sourcing (Scope 3).

To predict CO_2 emissions, data on recipe parameters and their influences have to be collected and provided in a unified and integrated form. Therefore, AAS structures as well as a specified green Digital Twin information model and database, are used (Wöstmann et al. 2022). In the next step, multivariate supervised machine learning models are trained on this data to estimate CO_2 emissions accurately.

The models consider factors such as process times and temperatures within the mashing, lautering, boiling, cooling, fermenting, and maturing, as well as the amount and PCF of hop, yeast, and malt. By adjusting recipe parameters within the models, brewers can generate optimized recommendations that minimize CO_2 emissions while maintaining product quality.

This data-driven approach enables continuous optimization of CO_2 emissions during early recipe planning (see Figure 3). By leveraging machine learning, brewers can make informed decisions to reduce the environmental impact of a brewed beer by, for example, adjusting recipe parameters or changing their raw material sourcing.

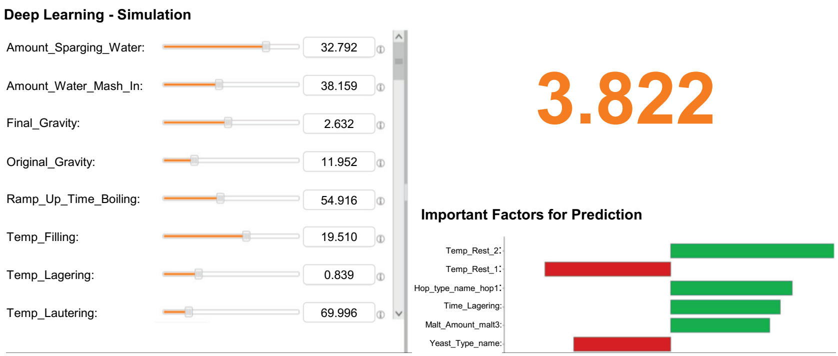

Figure 3: Recipe Simulator in RapidMiner

5.2. Flexible production planning for charging stations

The second approach reacts to flexible market conditions to create sustainable production planning. Planning production systems under flexible market conditions require a high level of interlinking between production planning and product development. This aspect is being analyzed for charging station assembly in the research project SimUltane Product and Process Development of a Charging Station Outlet Module Suitable for Automation (SUPPLy). For this purpose, the simulation model of a flexible-man-power line shown in Figure 4 was set up and analyzed using various configuration scenarios.

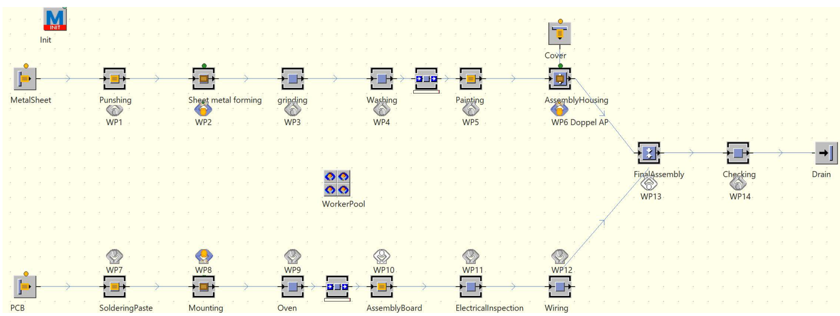

Figure 4: A simulation model of a flexible production line in Tecnomatix Plant Simulation

As can be seen in Figure 4, the line is equipped with workstations capable of human-robot interaction. Different line and organizational configurations can be analyzed in terms of output quantity based on other quantity requirements. The model also enables the output of energy consumption data based on current planning aspects.

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This data serves as feedback for product development with regard to product design. This allows optimization potentials to be quantified and evaluated in terms of their influence on production.

5.3. CO_2e reduction in cyber-physical brewing laboratory

In this approach, the green Digital Twin provides the foundation for visibility and transparency of energy consumption and emissions, which is the starting point for reducing CO_2e in production. The RIF and CAM UTS operate each cyber-physical brewing laboratory for data engineering and analysis. The challenge is to demonstrate and reduce CO_2e emissions while brewing beer based on energy-oriented Digital Twins for both locations.

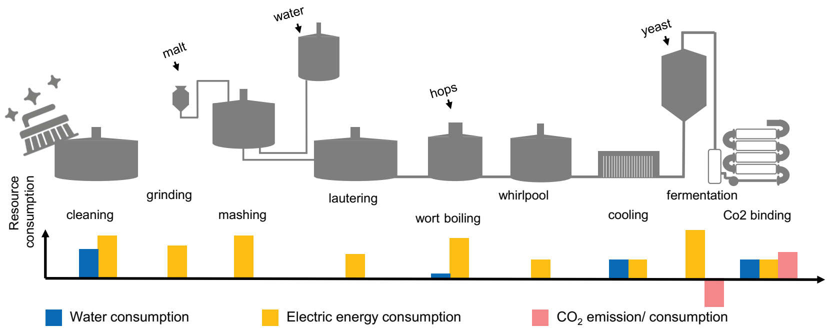

Figure 5: Concept for transparency in resource consumption

To achieve this goal, the green Digital Twin will collect data on energy consumption and emissions from various sources throughout the production process, such as electricity use, process heat, physical and biological processes and transportation. The challenge is integrating all data sources in the complete production system and developing semantic links between energy sources and sinks. This information model will enrich the green Digital Twin.

The next step will include energy and emission-oriented production planning and control of the cyber-physical brewing laboratories based on historical data. Using real-time data and forecast models, the intelligent control system in the green Digital Twin enables improvements in production program planning about emissions. The control system uses prediction models to communicate real-time optimization potentials based on CO_2e allocation to the brewers. The green Digital Twin is continuously monitored and updated by comparing simulation results with actual data. This enables identifying discrepancies and adjusting in real-time, ensuring the production process runs as efficiently and sustainably as possible.

In addition to monitoring emissions from the production process, the green Digital Twin will track excess CO_2 from the fermentation process. This excess can be sequestered into CO_2-binding biomass using a microalgae photobioreactor and reported into the software architecture of the green Digital Twin. A concept for a real-time connection between location-independent CO_2 emitting and compensating production systems was presented by the Estanium Association (Estanium Association 2023) with a photobioreactor operated by CAM UTS. This will enable stakeholders to track and optimize emission offsets (Deuse et al. 2022).

5.4. Refrigerating appliances recycling

An important aspect of the green Digital Twin is to ensure that no stages of the product life cycle are omitted (Wang/Wang 2019). Possible implementation methods and benefits of green Digital Twins at product's EOL are researched and demonstrated in the RIF e.V. project DiKueRec, which focuses on the refrigerating appliances recycling industry. This approach targets products already on the market that have not yet been subject to ecodesign and the integration of generic submodels.

Recycling old refrigerators plays a major role in protecting the Earth's atmosphere from ozone depletion and the emission of greenhouse gases. For instance, half of the handled appliances still contain volatile fluorinated and/or chlorinated hydrocarbons (VFC) (Deutsche Umwelthilfe 2016) with a global warming potential (GWP) up to 8100 times higher than the GWP of carbon dioxide (Abas et al. 2018).

The waste stream of old refrigerators is currently monitored and evaluated through manual records and lists. This is error-prone and prohibits input-dependent process efficiency control. Therefore, a significant potential exists in digitizing the incoming waste stream data to ease the workload of monitoring for the personnel and to introduce a modern energy efficiency control through green Digital Twins. (Polikarpov et al. 2022)

In the first step, an automated data collection system for recycling plants was proposed. Due to the long-life period of fridges, there is a lack of standardized information accompanying the products as their unified DPP is not implemented yet. The labels in the fridges are not easily accessible in recycling plant circumstances where short cycle times must be ensured. The labels are often not standardized and, in some cases, missing due to very long periods of use. The research project validated a retrofit solution using various sensors, including laser scanners and cameras in an IoT setting, to fill in the observed information gap (see Figure 6). The automated measurements of incoming fridges are utilized to create green Digital Twins containing attributes required for efficient control of recycling machinery (e.g., adjusting shredder power consumption to the fridge size, adjusting gas

DOI: https://doi.org/10.30844/wgab_2023_10

filter exchange periods based on the real number of processed fridges, etc.). Using artificial intelligence, green Digital Twins of recycled refrigerators support the calculation of expected material masses, especially foaming and cooling agents.

The comparison of the predicted collection values with the actual output of recycling plants leads to accelerated decision-making and a higher readiness of recyclers for environmental certifications of their plants.

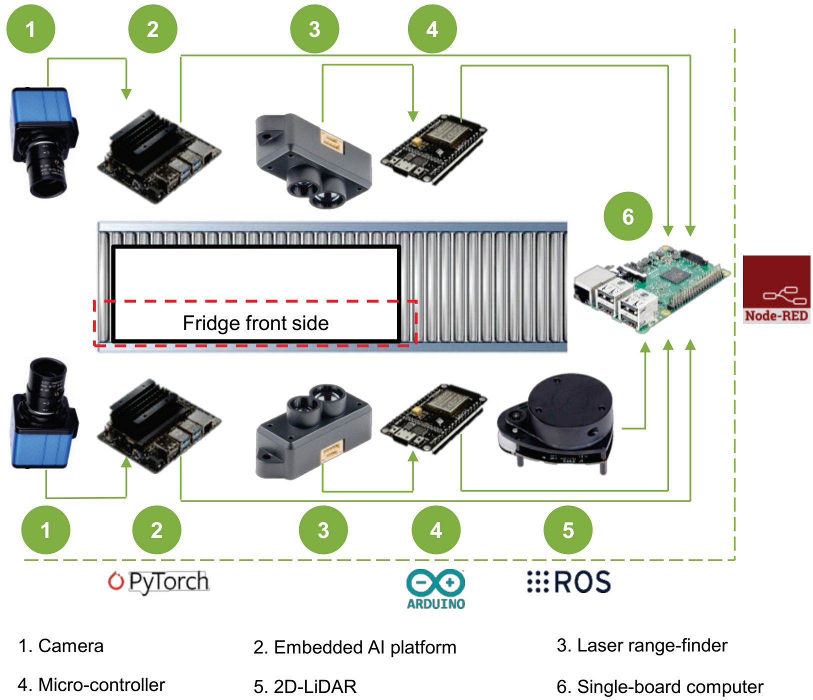

Figure 6: Prototype concept of the refrigerator scanning

Ideally, the information flow between the manufacturers, users, and fridge recyclers should fulfil the respective actors' information demands. Interest conflicts may appear, e.g., EOL actors may require information on product composition, but not all manufacturers will be ready to share this information (Plociennik et al. 2022). In the next step, the observations and the data structure behind the fridge green Digital Twin shall be used to ensure that fridge DPP contains sufficient data for recyclers that the manufacturers are also ready to provide.

The findings and the developments of the DiKueRec project emphasize the need for tight cooperation between manufacturers and recyclers to create a value-added green Digital Twin. For dealing with the existing product information gaps at the recycling stage, Industry 4.0 technologies and concepts can be applied to instantiate a green Digital Twin at the EOL for efficiency control and audit purposes.

6. Discussion and Conclusion

Green Digital Twins demonstrate immense potential in developing sustainable product life cycle management. The focus is to reduce industrial emissions and resource consumption with the help of Industry 4.0 technologies such as real-time data monitoring, machine learning models and simulation to optimize resource consumption and reduce CO_2e. In summary, the described approaches offer chances for improving Scope 1 and Scope 2 emissions, providing a holistic product design and production planning based on transparency in production, usage and EOL. The applications demonstrate green Digital Twins of various domains for each stage of the product life cycle with the potential to reduce climate-damaging actions. Sustainable recipe planning with green Digital Twins enables proactive prediction and optimization of CO_2 emissions during brewing. Integration of green Digital Twins in production planning enhances resource allocation and output optimization. CO_2e reduction in a cyber-physical brewing laboratory is achieved through real-time data collection and the optimization of production planning and control. Green Digital Twins facilitate efficient monitoring and control of the recycling process, improving energy efficiency and material mass calculation.

In conclusion, the contribution of this research highlights the significance of green Digital Twins in driving sustainable practices and reducing global industrial emissions. However, further investigations are vital to exploit its full potential. Specifically, the development of a generalized green Digital Twin is necessary to map semantic, statistical and external information effectively.

Further research and implementation of green Digital Twins are crucial for reducing global industrial emissions. A generalized green Digital Twin with semantic links needs to be developed to map semantic and statistical information. This semantic information model is the basis for performing what-if scenarios and enriches existing information.

To advance this field, future work will involve defining the requirements for building use case-specific and modularized semantic information models. These models will serve as the foundation for conducting what-if scenarios and enriching existing information. By integrating semantic knowledge as well as statistical and external data, industries can gain deeper insights to enhance sustainability efforts.

DOI: https://doi.org/10.30844/wgab_2023_10

Acknowledgements

This paper presents the research projects DaPro, SUPPLy, BeverGreen and DiKueRec.

The research and development project "Data-driven process optimization using machine learning in the beverage industry" (DaPro) is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) within the program "Smart Data Economy" (grant no. 01MT19004D) and managed by the DLR.

The project "SimUltane Product and Process Development of a Charging Station Outlet Module Suitable for Automation" (SUPPLy) is supported by the German Federal Ministry for Economic Affairs and Climate Protection (BMWK) on the basis of a decision by the German Bundestag (grant no. 01MV19001B).

The research and development project "Green Digital Twin as the Foundation for the Sustainable Transformation of the Beverage and Brewing Industry" (BeverGreen) is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) in the program "GreenTech Innovation Competition" (grant no. 01MN23008C) and managed by the German Aerospace Center (DLR) project sponsor.

The research and development project "Utilization of digital twins for efficient control of recycling processes in the use-case of refrigerating appliances recycling" (DiKueRec) is funded by the German Federal Ministry of Education and Research (BMBF) within the Action Plan "Natürlich.Digital.Nachhaltig" (grant no. 02WDG016D) and managed by the Project Management Karlsruhe (PTKA).

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Industrial management is facing many challenges, one need is to adopt sustainable practices. As climate change is becoming an increasingly urgent problem, industrial management must find ways to reduce waste and pollution, conserve natural resources, and protect the environment and employees. Industrial management also needs to embrace new technologies like virtual reality, artificial intelligence, and the Internet of Things. These challenges are becoming more prevalent, managers and decision makers must find ways to adopt these new technologies in order to remain competitive. Furthermore, with the workforce becoming more diverse and globalized organisations have to attract and retain top talent. For industrial management it is important to create an inclusive work environment. Current research approaches from the members of the Scientific Society for Work and Business Organisation (WGAB) are presented in this book.

ISBN 978-3-95545-412-8

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