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Methodical Implementation Of Digital Data Consistency In Assembly Lines Of A Learning Factory

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Abstract

The possibility of acquiring data in production and manufacturing processes is almost limitless. But especially small and medium-sized enterprises (SMEs) lack the knowledge to successfully integrate digital tools and use real-time production data for critical decision-making. Numerous initiatives already exist to inform and support SMEs in Germany, funded at various levels by municipal, federal, and state entities. These initiatives offer expertise in digitalisation and provide diverse activities to support SMEs across different industrial sectors. To make abstract concepts such as artificial intelligence (AI) or digitalisation more tangible, demonstrations and practical best practice showcases demonstrate methodological approaches for facilitating independent implementation initiatives within SMEs. However, most of these activities primarily showcase rudimentary and isolated technological implementations, with limited integration into the complex environment of a manufacturing company. This paper focuses on a holistic methodical brownfield implementation of a demonstrator for digital data consistency in an assembly line of a learning factory by applying an extended methodology for implementing demonstrators and its validation by industrial participants. It stresses the complexity of production data acquisition in a practical environment and illustrates a best-practice showcase. Key performance indicators are visualized by acquiring, storing, and cross-linking data points. The demonstrator is implemented and evaluated by SMEs' representatives, to show promising potential for sustainable knowledge transfer into the SMEs.

Keywords

digitalisation; industry 4.0; production data acquisition; factory planning; machine learning; learning factories, demonstrator

1. Introduction

Exploiting a company's value creation potential within production sites is paramount in achieving substantial revenues. The utilization of digital tools becomes crucial for the enhancement of lean implementation as well as decisions with great impact, as they provide real-time data for informed decision-making [1]. This data needs to be extracted from machines (machine data) or processes (operating data) at essential information points and serve as data points to establish transparency by key performance indicators (KPIs) [2]. Especially small and medium-sized enterprises (SMEs) often lack such implementations of data usage in their production sites [3]. Consequently, decision-making tends to be delayed or based on inaccurate assumptions due to the absence of transparency in value-creation processes [2]. Existing initiatives of various centres of competence funded on municipal, federal, and state levels already assist SMEs on this matter by informing companies on digitalisation or artificial intelligence (AI) and showcasing best practice use cases to make these topics tangible [4]. Such demonstrations tend to be downscaled or simplified for better understanding and were developed as greenfield implementations [5–7]. Furthermore, existing brownfield

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concepts often prioritize hardware infrastructure and production processes and do not consider the extension of existing IT infrastructure [8]. The object of research, presented in this paper, is a solution which can be easily transferred to SMEs thus ensuring an applicable transposing of production processes. Following the established learning factory (LF) approach [9], using realistic and industrial-like surroundings for best transfer results, the existing infrastructure of the Learning and Research Factory (LFF) of the Chair of Production Systems (LPS) at the Ruhr-University Bochum [10] was extended. Consequently, a demonstrator for digital data consistency is methodically developed, focusing on assembly lines as an illustrative example. An extension of the existing methodology for a demonstrator's brownfield implementation into an existing environment constitutes the primary emphasis of this paper. The functional implementation of the demonstrator serves as the extended methodology's proof of concept. Validation is then conducted through integration into informational events and subsequent surveys. However, it is important to note that the validation is not part of the methodology itself and paper does not address the comprehensive development of a competency-based LF environment (LFE) for action-oriented learning.

2. Fundamentals

2.1 Learning factories and demonstrators

LFs provide hands-on and experimental training for students and industrial employees. These facilities aim to replicate industrial settings, allowing participants to acquire practical knowledge and skills in a controlled and safe environment. [11] A comprehensive classification morphology has been developed to describe different types of LFs. Initially introduced by TISCH ET AL. [9], this framework has recently been updated and expanded to a total of eight dimensions [12]. Of relevance to this paper and therefore to the implementation of a demonstrator, are the dimensions of process, setting and product, as they describe the environment of a LF. The LFE includes the overall physical or virtual setting that emulates a real industrial or manufacturing workspace. It consists of various workstations, machinery, equipment, and resources that replicate those found in actual industrial settings. This LFE is designed to fulfil the didactical requirements as a secure and controlled space for this purpose. It enables participants to acquire knowledge and skills related to production processes, production management, digitalisation, automation, and related areas [13].

On the one hand, demonstrators are typically characterized as model-scale environments [5] and are interpreted in this paper as components within an existing or future LFE. They serve to represent specific technologies, processes, and best practices, or provide foundational information on various topics [13]. These segregated systems offer participants hands-on experiences and facilitate a deeper understanding of the practical applications of the technologies being showcased. Demonstrators play a crucial role in bridging the gap between theoretical knowledge and practical implementation and are frequently utilized in knowledge transfer initiatives such as the "Mittelstand-Digital Zentren" in Germany [14]. Demonstrators can be categorized as either material or non-material manifestations. Materialistic demonstrators can be either mobile [15,7] or stationary [6,8]. On the other hand, the LFE in the narrow sense encompasses the broader setting that replicates an industrial workspace and provides a comprehensive learning experience with various workstations and resources [16].

2.2 Existing design approaches for demonstrators

Various design approaches have already been established for the development of LFEs. One comprehensive approach, pioneered by Tisch et al. [9] and used most often [17], focuses on creating a LFE that offers direct applications of competencies for extensive learning modules. This approach contains two didactic transformations. The first didactic transformation encompasses organizational requirements and learning objectives, while the subsequent stage involves the configuration and implementation of the didactic and sociotechnical infrastructure. Another approach, which builds upon TISCH ET AL. [9], specifically addresses the development of a mobile demonstrator [7]. Additionally, there is an effort to create a model scale environment tailored to enhance energy efficiency [5] or a demonstrator's framework in cyber-physical production systems [18]. The application of a reference architecture for demonstrators [19] does not match the usage of demonstrators as mentioned above, but the simulation of new cyber-physical systems. Consequently, a gap exists in the existing methodology when it comes to the technical implementation of demonstrators as a preliminary step within an already established hardware and software infrastructure.

2.3 Learning factory evaluation

To ensure the success of a demonstrator and its effectiveness in illustrating specific information to participants, evaluation is essential. When assessing the success of LFs, the Kirkpatrick Model [20] is frequently used already [21]. The Kirkpatrick Model is a widely recognized framework for evaluating the effectiveness and impact of training and development programs. This model provides a systematic approach to evaluating training outcomes across four levels. The first level focuses on participants' immediate reactions to the training program. It measures their satisfaction with the training, their perception of its relevance, and their overall engagement. Feedback is typically gathered through surveys and questionnaires. The second level assesses the extent to which participants have acquired new knowledge, skills, or competencies because of the training. It measures the increase in participants' knowledge and understanding. The third level of evaluation examines the extent to which participants apply the newly acquired knowledge and skills in their workplace. The highest level of evaluation focuses on the overall impact of the training on the organization's outcomes. Considering that demonstrators primarily serve as a form of learning but may not address high-level competencies [13] due to their limited interaction period with participants, this paper focuses its evaluation on the initial reactions and low-level learning outcomes [20]. Specifically, it examines the taxonomy levels of remembering and comprehension [22] in stage two.

3. Methodology

The foundations for the systematic development and implementation of a LFE have already been established [9], and there are already comparable instances of mobile [7] and stationary demonstrations that have built upon this foundation. The subsequent chapter describes the extension of the existing approach, including the necessary adaptations to meet the given specific use case, which entails integrating a demonstrator into the existing hardware and software infrastructure and surroundings within a brownfield LFE. The pre-existing design approach of a first and second didactic transformation is still the macro-structure. However, adjustments to align this approach with the technological focus of the demonstrator are made. Considering the requirements of a practical demonstrator, alongside the extensive implementation within an existing operational infrastructure, more comprehensive guidance is relevant for the conception and execution phases. This can be accomplished by complementing the existing approach with the incorporation of the VDI 5200 [23] guideline for factory planning (see Figure 1).

4. Implementation

4.1 Phase 1 – setting of objectives

The main target groups for the demonstrator primarily comprise representatives from SMEs. Their professional roles include digitalisation officers, process engineers, plant managers, and potentially other positions. The second group consists of multipliers, such as chambers of commerce, associations, and consultants. Each target group has distinct transfer objectives, which are further categorized as primary and secondary objectives (see Table 1). The primary objectives aim to generate participants' interest and foster their understanding of the functionality of live data acquisition, interfaces, and the steps involved in establishing KPIs, using the demonstrator as a best practice example. Moreover, the secondary objectives aim to encourage SMEs to take further steps towards implementing similar digitalisation practices in their production processes.

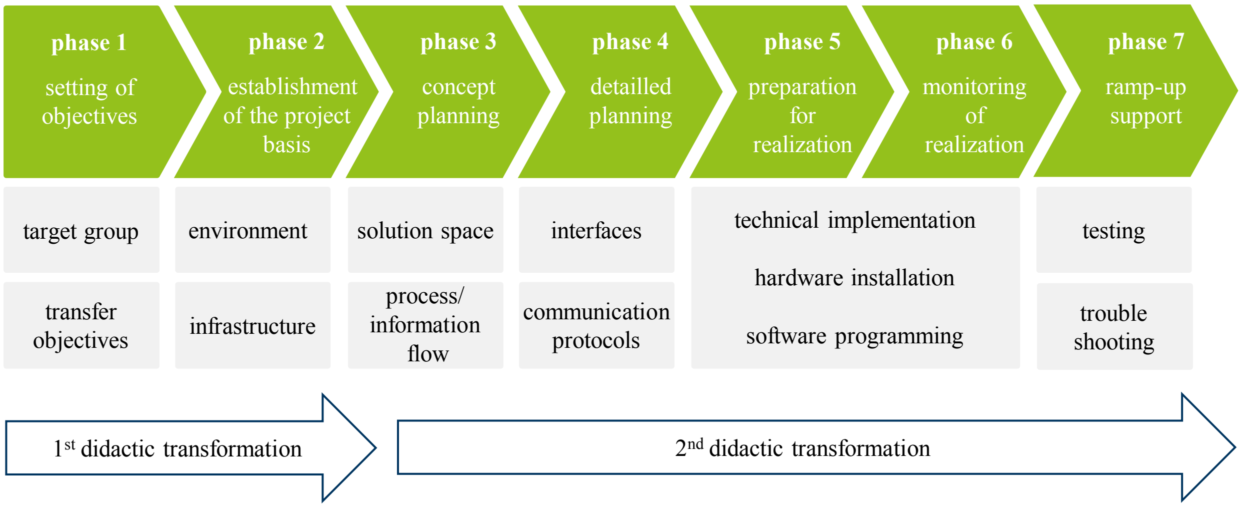

Figure 1: Phase model of a demonstrator's brownfield implementation following TISCH ET AL. [9] and VDI 5200 [23]

It is important to note that other groups, such as students or works councils, are not listed as primary targets, as their specific transfer objectives may differ from those of the primary target groups. The transfer objectives play a crucial role in evaluating the demonstrator later. They were developed in discussions with the target groups and condensed in expert brainstorming sessions.

Table 1: Target groups and transfer objectives of a demonstrator for digital data continuity

target groups	primary transfer objectives	secondary transfer objectives
digitalisation officers, process engineers, plant managers, etc.	• Generating participants' interest in live data-driven KPIs • Understanding the concept and functionality of the demonstrator • Understanding the basic digitalisation phases • Increase in understanding of digital data continuity • Stressing the variousness of interfaces and the system's entities	• Initializing digitalisation efforts by showcasing best practices • Raising awareness of the challenges and complexity of digital data continuity • Supporting SMEs initiatives for digitalisation • Increasing transparency and data-based decision-making in manufacturing SMEs
multipliers, industrial chambers of commerce, associations, etc.	• Showcasing best practice examples for digital data continuity • Train-the-trainer format in digitalisation of production sites	• Creating a presumption of competence to hold joint events • Multiplying gained impressions to manufacturing SMEs

4.2 Phase 2 – establishment of the project basis

To address the transfer objectives, various hardware and software solutions already exist. By integrating the new demonstrator into the existing infrastructure, investments and efforts can be reduced by selecting the most suitable project foundation of already existing hard- and software. Three potential scenarios are considered within the LFF: a hybrid assembly line [24], a terminal strip assembly line with real production orders [25], and the UniLokk bottlecap assembly line [26]. These scenarios are listed and compared, highlighting the pros and cons of each (see Table 2). All the scenarios can equally leverage the established IT infrastructure of the LFF, which encompasses essential components such as a router for the communication standard Open Platform Communications Unified Architecture (OPC UA router), a

Structured Query Language database (SQL database), and a broker of the message protocol Message Queuing Telemetry Transport (MQTT-Broker). Among these options, the UniLokk assembly line presents the most compelling advantages. It mostly captivates with the existing track and trace system, and cognitive worker assistance systems, incorporates AI for object detection and quality management [26], and offers various human-machine interfaces (HMI). These features provide a well-suited project foundation for achieving the desired transfer objectives (see Table 1). The setup consists of three assembly stations (see appendix Figure 3 and Figure 4). The first station serves as a preassembly area where the worker (1) is responsible for glueing tasks. In the subsequent station, worker (2) assembles the pre-assembled component from station one along with the remaining UniLokk components. Following the hardening process, worker (1) transitions in the meantime to station three to conduct quality inspections on an assembled UniLokk before packaging the final UniLokk product and moving back to station one for finishing the preassembly.

Table 2: An overview of the advantages and disadvantages of given assembly line scenarios in the LFF

scenarios	pro scenario	contra scenario
COssembly (hybrid assembly line)	• Already existing digital twin • Machine data of robots available • Production data is available	o Very complex system o Complex start-up procedures for hard- and software o No database connected
terminal strip assembly line	• Manufacturing execution system already integrated • Order production for customers • High amount of production data (also used for research)	o Interference with production results in loss of piece numbers o Interference with production results in falsified research results
UniLokk bottlecap assembly line	• Isolated digital applications already exist (AI object detection, track and trace system) • Versatile product with most frequent use in other transfer events, formats and topics • Various cognitive worker assistance systems exist (pick-to-light system, HMI-based, etc.)	o No database connected o No interfaces or connections to frontends exist o Lean processes via paper

4.3 Phase 3 – concept planning

Enhancing the transparency of the UniLokk assembly line includes gathering target KPIs and extrapolating the general functionalities of the demonstrator. Relevant data points of each assembly station are listed in Figure 3 in the appendix. An overview of the approximate function and information flow is depicted in Figure 2. The flow traverses the primary dimensions, including the human dimension, the human-machine interface, and the cyber-informatic dimension. These flows will be elaborated in greater detail in phase 4.

4.1 Phase 4 – detailed planning

Subsequent planning efforts yield a comprehensive draft outlining the detailed information flow (see appendix, Figure 5). This precise depiction describes the specific dimensions and processes involved in customer interaction and worker assembly. The digital dimensions are derived from the digitalisation phases outlined in the acatech phase model [27], differentiating between data collection, data processing, data provision, data storage, data visualization, and data analysis or prediction. Each station of the UniLokk assembly line is equipped with radio frequency identification (RFID) scanners to facilitate seamless and contactless tracking of the product. The RFID chips' identification number captured by the scanners is processed through their programmable logic controllers (PLCs) and afterwards mapped by the OPC UA router to ensure efficient signal transmission. To showcase the capability of utilizing two frequently used communication standards in production digitalisation, the OPC UA router further processes the signals into the MQTT protocol, which is then published by the MQTT broker. Open-source software, such as node-red,

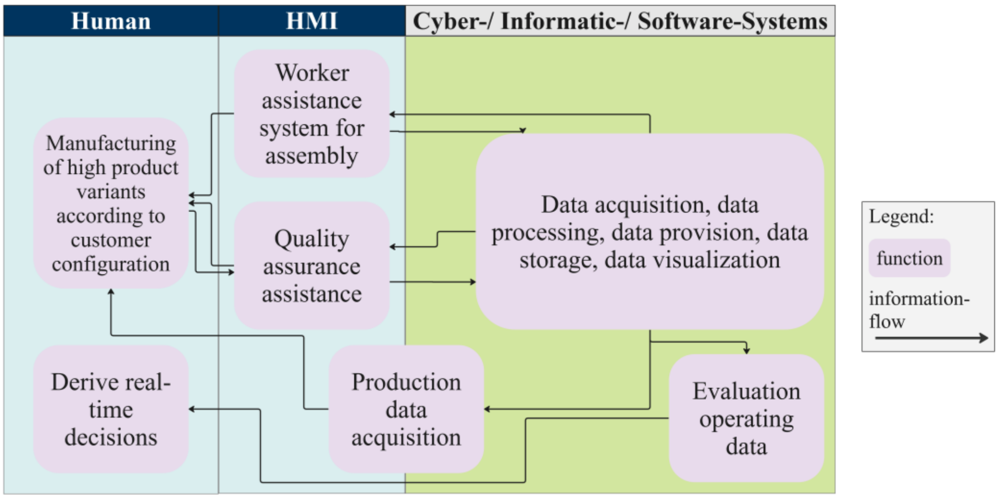

Figure 2: Concept planning of a digital data consistency

incorporates various programs and flows to assimilate the data and write it into the database. Additional node-red flows provide diverse front-end interfaces customized for both workers and plant managers on screens, featuring different KPIs. The application of the YOLOv7 AI algorithm [28] enables object recognition via camera, providing relevant data for comparing the manufactured product with the customer configuration. However, beyond this specific function, no further data analysis or prediction is conducted. It is important to note that the interpretation of the dashboard data by the plant manager or worker is not depicted in Figure 5. Lastly, each RFID chip, which identifies the current product in each station, triggers a pick-to-light flow to guide the worker in picking the appropriate parts.

4.2 Phases 5, 6 and 7 – preparation, monitoring of realization and ramp-up support

The hardware yet to be acquired was obtained through offers and procurement requests. The execution of the project involved a collaborative effort among students undertaking their final theses, research assistants, technical personnel, and academic staff. All persons involved worked together on parallel tasks or coordinated milestones. The collaboration involved interdisciplinary teams composed of students specializing in applied informatics, electronic engineering, automation engineering, and process management. These teams worked together to synchronize their efforts and ensure smooth integration among the various components of the previously described system architecture. A conventional ramp-up process is dispensable due to the non-commercial and non-value-added utilization of the demonstrator's environment. However, despite this fact, a series of stress tests and iterative optimization cycles remain essential even post-realization. The demonstrator's content has been integrated into the operational flow of the pre-existing technology tour. The initial application and evaluation for project assessment are conducted within this phase but will be dealt with in the subsequent chapter.

5. Application and evaluation

5.1 Application of the demonstrator

The proof of concept was assessed during organized events hosted in the LFF. The target audience for these events consisted of employees from SMEs who participated in technology tours offered free of charge as part of externally funded transfer projects [14]. These tours serve as a platform to provide participants with first-hand exposure to state-of-the-art technologies. The insight is facilitated through research cells or demonstrators. During these technology tours at the LFF, participants receive basic knowledge of technologies, as well as principles related to digitalisation, AI, automation, and robotics. To augment the participants' understanding of the digitalisation of production data, the implemented demonstrator for data consistency in assembly lines has been integrated into the tour. This integration allows for a more comprehensive and immersive experience, enhancing the participants' superficial understanding of the subject matter.

Initially, participants were provided with fundamental knowledge about the acatech phase model [27] and its phases related to digitalisation and Industry 4.0. They were immersed in a scenario involving a fictional SME engaged in the production of the UniLokk. The basic assembly process of the product was illustrated across three stations, prompting the participants to contribute their ideas regarding KPIs relevant to the assembly lines through a collaborative brainstorming session. Together, they identified the need for feedback on productivity, efficiency, and transparency. The resulting KPIs aligned with the objectives defined in Chapter 4, including metrics such as the number of units, quality rates, and cycle times. Instead of developing a technological solution concept from scratch, the participants were introduced to the fully implemented demonstrator that served as a best-practice example. Each aspect, system component, and software interface were described to the participants by the event host of the LPS. Following the introduction, the participants were given the opportunity for hands-on experience. They engaged in activities such as entering customer orders, initiating production orders via RFID chips, operating the optical quality control, and submitting quality data through the HMI. Through these interactions, each participant gained insights into the information flow of every actuator and sensor. The hardware components, such as scanners and PLCs, were visually illuminated to indicate the acquisition and transmission of data. The data flows were then visualized within the system's components, including the OPC UA router, MQTT-broker, node-red backend, node-red frontend, and SQL database. Feedback was conveyed through visual changes in various options, such as debugging messages, colour modifications, or the addition of characters.

5.2 Evaluation of the demonstrator

Upon completion of the testing phase, each participant was requested to complete questionnaires as part of the evaluation process for the demonstrator. As the current classification categorizes the event as an informational session, the primary objective is not focused on profound competency development. The questionnaire was developed based on the Kirkpatrick approach [20], only focusing on levels one and two. The main content of the surveys deals with the predefined objectives established before the planning phase. Section one of the survey refers to the participants' subjective assessment of their comprehension of the first level of Kirkpatrick's evaluation framework. The questionnaire specifically asks participants to self-assess their interest in digitalisation within assembly lines, as well as their perception of the complexities surrounding data collection and distribution for visualization purposes. Additionally, it evaluates their reaction to the effectiveness of the demonstrator in clarifying relevant functions, the participants' understanding of data acquisition processes, and their comprehension of the overall system architecture. Section two examines the participants' understanding of the demonstrator's functionality, ranging from Anderson's levels of remembering to comprehension, through a series of targeted questions, like the sequence of the digitalisation phases, the relevance of software interfaces and other aspects of the demonstrator’s functionality. In the third section, the success of knowledge transfer is assessed by a request for feedback on the emergence of inspiration. This section primarily focuses on comparing existing aspirations for digitalisation in assembly lines, existing use cases, and participants' interest in commercial or prototypical implementations. It is worth noting that each question allows for abstention, providing participants with the option to decline to respond if desired. Sections one and three consist of scale questions, requiring feedback ranging from 1 (strongly agree) to 5 (strongly disagree), including the option to abstain. Additionally, section four collects data on participants' backgrounds, such as their industry, number of employees, and role within their companies. The survey results are presented in Figure 6 of the appendix. A total of 19 surveys were collected and the survey’s questions are numbered in their section. Outliers are indicated by dots on the graph. Three surveys were excluded from the evaluation in section three, as the secondary target group did not possess aspirations for transfer goals due to the absence of manufacturing applications in their companies. These individuals did not abstain from providing feedback, which is why their responses were not considered. Overall, the reactions in section one rank in the higher categories, except for question 1.6. This question served as a negated control question to prevent any potential falsified results and is opposite to that of the other questions. The distribution of correct and incorrect answers in section two also reveals the most correct responses, with approximately 15.8 % abstentions and 26.3 % incorrect answers combined across all four questions. However, the feedback regarding transfer goals demonstrates a wider range of opinions. These numbers do not directly align with the positive feedback received in section one. The discrepancy observed in question 3.2 indicates a lack of knowledge among participants or no applications at all regarding the existence of comparable use cases within their companies.

6. Conclusion and outlook

The primary objective of this paper was to methodically implement a low-threshold demonstrator for digital connectivity and data continuity in assembly lines, laying the groundwork for knowledge transfer to SMEs. Existing approaches fell short of meeting the requirements of industry-oriented integration of demonstrators within the existing infrastructure of the LFF. Consequently, the existing concept was enhanced by incorporating a guideline for factory planning projects. The usage of the demonstrator in information events focused on stimulating digitalisation efforts in SMEs at lower taxonomy levels. The initial proof of concept yielded positive feedback on the demonstrator's set-up and illustration of digitalisation on assembly lines in an existing brownfield IT infrastructure. With most correct answers obtained on the lower levels of taxonomy, the demonstrator successfully meets the established requirements, indicating its promising potential for future application. However, it is important to note that the demonstrator does not fully eliminate all existing barriers inhibiting SMEs on their own comparable projects in their production, as evidenced by the mixed feedback on transfer. This emphasises the current limitations of the demonstrator concept and stresses the necessity for comprehensive competency development within SMEs.

Ongoing evaluation will play a crucial role in further developing the demonstrator and improving the current information format. A new evaluation category could be introduced to assess the industry-like format of the demonstrator and ensure its practical orientation. Additionally, a more detailed information module could equally balance technology and methodology by integrating the guideline for factory planning. Moreover, there is room for enhancing participant involvement. By implementing further didactical and technological improvements, such as incorporating new data points or applying data analytics, new qualification modules can be developed. These modules would focus on the profound application of methods, such as *value stream mapping 4.0 plus* [29] or digital shopfloor management, at higher taxonomy levels and foster competency development in digitalisation. The demonstrator can serve as an appropriate LFE for such advanced modules. Furthermore, the effect of the demonstrator on heterogenous target groups from different SMEs with differing employee numbers, professions and industries still has to be examined as the number of participants is not high enough at this moment.

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Appendix

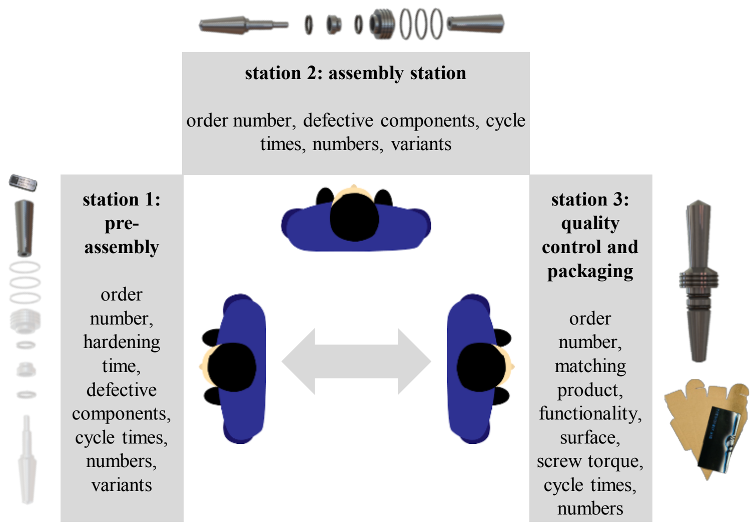

Figure 3: Schematic representation of the UniLokk assembly line

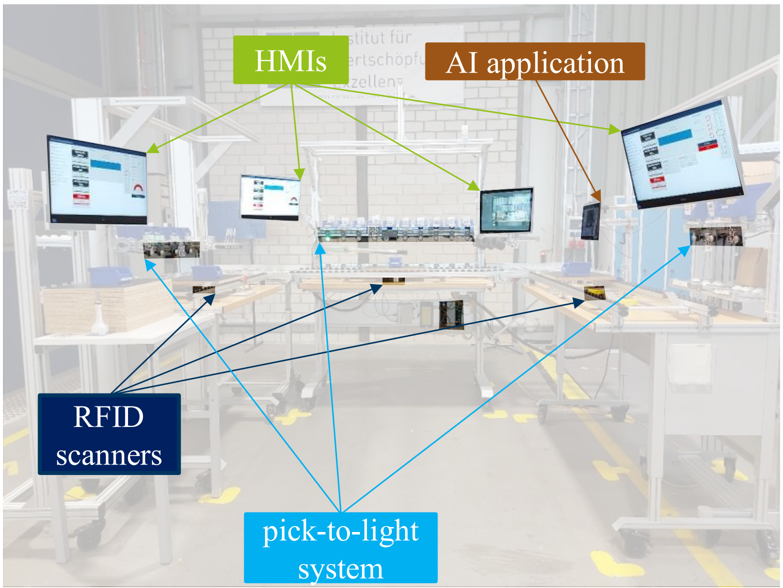

Figure 4: Hardware infrastructure of the UniLokk assembly line with HMIs, pick-to-light system, AI application and RFID scanners

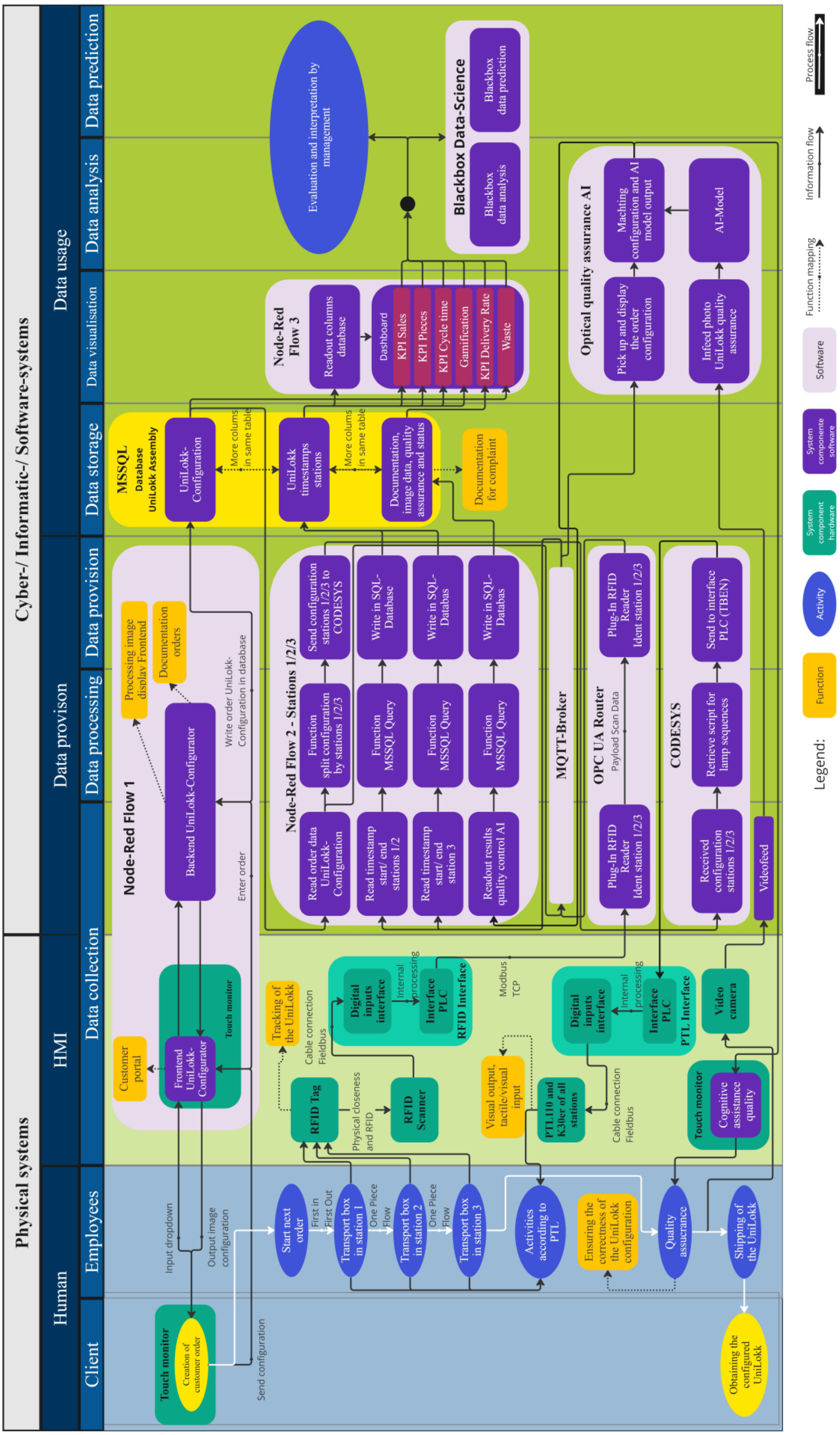

Figure 5: Detailed planning of a digital data consistency

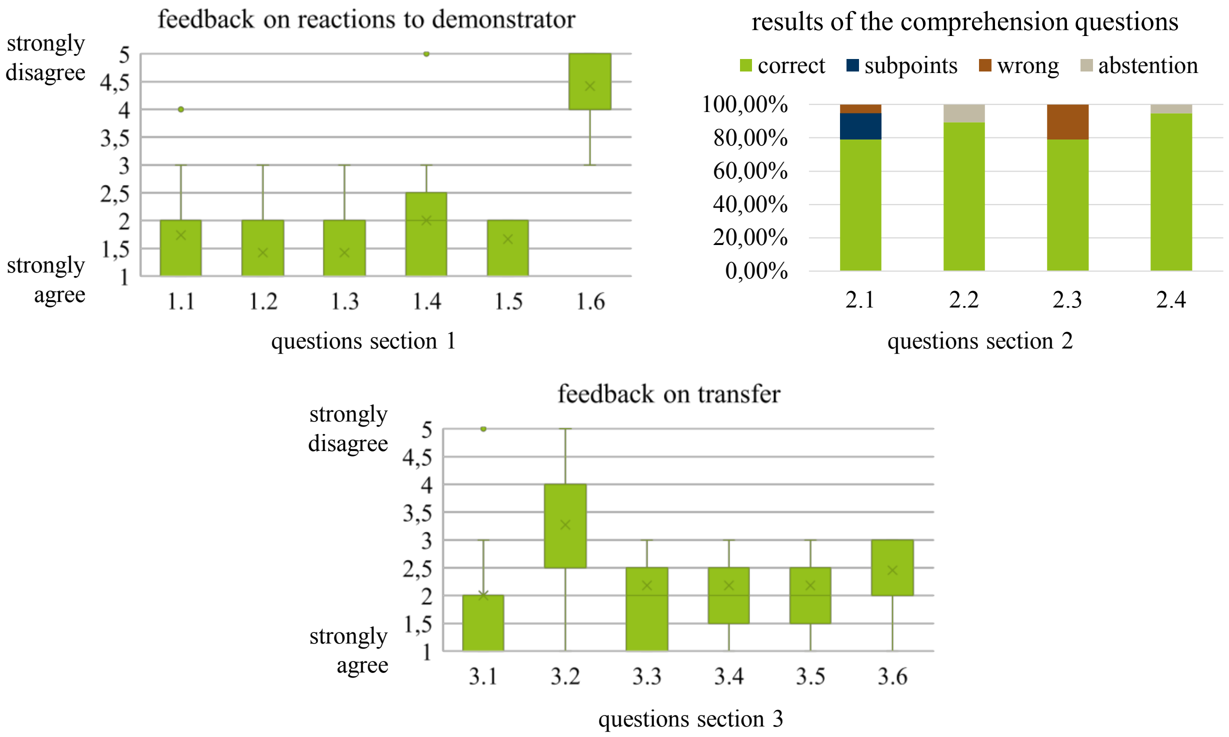

Figure 6: Results of the survey (section 1: n = 19; section 2: n = 19; section 3: n = 16)

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Biography

Marius Knott (*1993) has been working as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2020 in the field of production management. He earned a master's degree in mechanical engineering at the Ruhr-University Bochum. His primary research topic is the development of LFs and assumes the role of coordinator for the LPS' learning and research factory.

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Christopher Prinz (*1985) studied mechanical engineering at the Ruhr-University Bochum. After receiving his doctorate in 2018 on the topic of knowledge management in production, he was named Academic Advisor at the Chair of Production Systems (LPS). As part of the chair management, he is responsible for the strategic development of the chair and the initiation and control of research projects.

Until 2009 **Bernd Kuhlenkötter** (*1971) was responsible for product management and technology at ABB Robotics Germany. In 2009 Bernd Kuhlenkötter took over the professorship for "Industrial Robotics and Production Automation" at the Technical University of Dortmund. Since 2015 he holds the professorship of the Chair of Production Systems (LPS) at the Ruhr-University Bochum and is managing director of the Institute for the Engineering of Smart-Product Service Systems.