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Digital twinning as the basis for integration of education and research in a learning factory

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Abstract

Learning factories that focus solely on education may benefit from replicating software systems that drive processes, activities, and workflows in industrial environments. However, such systems (e.g., PLM, ERP or MES) will not meet the requirements if the learning factory intends to be an environment where education and research merge. The flexibility, volatility, ambiguity and incertitudes that characterise the integrated learning-research environment need to be addressed with an approach that replicates industrial reality, but that also accommodates and stimulates the versatility of the learning factory. This paper depicts how the digital twinning approach integrates the physical units of a learning factory and the software systems, but also data acquisition, simulation, and educational/didactic approaches to production/assembly processes and production optimalisation. The approach thus also includes, for example, IoT, planning, monitoring, diagnosis and (quality) control. In addition, the digital twinning approach is used to combine the current state of the learning factory and its activities with designed (to-be) and potential (could-be) representations of the environment in order to stimulate the evolution/improvement of both research and education and their combination. For this purpose, digital twinning is combined with the concept of daydreaming. The paper illustrates the approach based on an ongoing development trajectory of a new learning factory, in setting it up as an environment for education and simultaneously as a testbed for research. It discusses how the development process relies on the digital twinning approach and how, when the learning factory is commissioned, this digital twinning approach will increasingly integrate the use of and activities in the learning factory into the development/evolution cycle of that learning factory.

Keywords: Learning factory, Digital twinning, Daydreaming factories, Education, Synthetic environments

1. Introduction

In settled manufacturing environments, the primary objective of operational management is to ensure that the primary processes run correctly, reliably, and predictably. Any change in, for example, product portfolio, settings, planning approaches or available assets is considered with the utmost care to avoid disruptions or inconsistencies in the supply chain. Typically, the established and proven conditions and approaches are captured and aligned with the many information systems used in the company. These systems, such as PLM, ERP, MES and CAQ systems, collectively provide a digital infrastructure tailored to the current state of the business [1]. While the interaction between these systems and the activities on the shop floor contribute to the robustness of the primary processes, these systems can also make the environment rigid and inflexible. In several cases, such systems actually ordain or dictate rather than support the primary processes. This can hamper the introduction of new technologies, assets, different working methods, and the training of new staff – to name but a few. Consequently, it impedes production development in general and attention to perspectives such as digitalisation or sustainability. At the same time, companies are aware that they can thrive on the possibilities provided by, e.g., digitalisation, new technologies and new employees. However, they need to explore how to evaluate and integrate these opportunities

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without compromising the primary processes. There are many approaches to this, such as daydreaming factories [2], what-if analyses, learning factories [3, 4], and pilot production plants [5, 6]. In all these approaches, the overarching hypothesis is that the current situation is sufficiently manifest to be extrapolated to represent potential futures. Moreover, it is pivotal to reason from the information content, rather than from the course of activities/processes to represent the current situation [6]. This publication explores, in a research-through-design approach, the development, evolvement and deployment of a learning factory as a flexible, agile, configurable counterpart to manufacturing environments. In this, the learning factory can alternatingly mimic, extend, complement, or provide alternatives for an existing or envisaged manufacturing environment. The research, with a time horizon of several years, focuses on the design, development, and implementation of a production environment. This publication outlines the guiding principles for this development path, while at the same time evaluating experimental setups that have been and are being used to gain insights and experience into the principles underlying this learning factory. Specifically, three objectives are addressed:

- To explore potential futures in a risk-free environment;
- To address stakeholder perspectives, without being constrained or directed by underlying information systems;
- To integrate the exploration of potential futures with the ability to train/educate all types of learners.

1.1. Approach

Industrial production environments are highly complex, connected, intertwined, and optimized networks of processes and information flows. However, both in academic education and research, a certain level of adaptability and uncertainty is required to understand dependencies and sensitivities. That understanding can then lead to further optimization and the introduction of, for example, new assets or technologies. In a sense, a ‘snapshot’ of the current situation in the production environment is needed as the backbone for interpretation and reasoning – without the risk of impeding the primary processes. Even if making such a ‘snapshot’ is possible, it would outdate extremely fast, and it would not allow for assessing the consequences of scenarios/decisions. For that reason, a digital twinning approach (see section 2) is employed here, that adheres to the current situation, and allows for interaction with potential or envisaged future situations. To create, develop and assess such potential futures, both a physical and a virtual simulation environment are introduced, integrated into a synthetic environment. The physical environment relies on the learning factory concept (see section 3), and the simulation environment relates to the daydreaming concept (see section 4). Conjointly, the physical and virtual environments allow for a combination of education and learning (see section 5). The information base that represents a realistic environment simultaneously acts as a study landscape for beginning learners to analyse, immerse in, and interact with established concepts, thus generating data/information that provide input for advanced learners and researchers in their efforts to optimize, improve, and develop.

2. Digital Twinning

The basis for any analysis of an existing industrial environment is a ‘snapshot’ of that environment; a digital twin is an excellent basis for this. In this context, a digital twin is a representation that digitally captures the current and past states an entity [7]. Such digital twins are instrumental in operational processes and for the collocation of the information systems in a company. However, to avoid impeding primary processes, a digital twin should not concurrently capture current conditions and potential and intended states. Consequently, the notion "digital system reference" [8] is used here. This digital system reference consists of three components: the digital twin, the digital master, and the digital prototype. The digital twin represents the current state of a system through data, information, models, methods, tools, and techniques. The digital master reflects the envisioned state of a system. The digital prototype allows for the exploration of future states of a system based on models, simulations, and experience, linking the digital master and the digital twin. It allows for assessing different scenarios and serves as a link between the "as-is" and "to-be" models, representing the "could-be" state. This "could-be" state allows for purposeful depictions of, for example, pilot production environments [6], in which the repercussions of alterations to the actual environment can be assessed. What-if questions that drive such alterations can stem from different perspectives involved in the environment, ranging from factory-layout to process planning and quality control. Such questions can be posed by experts seeking to explore specific conditions; yet, what-if questions can also be an excellent way of providing learners at varying levels/maturities with an evolving foundation for improved understanding and insight.

Where the digital twin component of the digital system reference closely relates to real, physical artefacts and actual processes in the production environment, the digital prototype and digital master thrive in virtual or augmented reality representations. Such extensions of the real world in a synthetic environment underline the ability to immerse in potential futures, involving users from different perspectives in more effective and efficient analyses and decision making.

In digital twinning, digital twin/master/prototype is considered a recursive entity, implying, e.g., that a digital twin consists of digital twins. Each can be addressed separately, and has distinctive behaviour, but is an inherent component of an overarching digital twin, through which it is connected to other entities. As a result, the digital system reference can be targeted to specific stakeholders, for a specific part of the overall environment and at the appropriate level of aggregation.

3. Envisaged learning factory

In existing, industrial, environments, digital prototypes and digital masters foremost add to digital twins – simply because running primary processes do not allow for bi-directional interactions. Yet, much research and education relies on physical entities, not only to produce/assemble products, but also for sensoring, testing and validation purposes. This implies that both learners and researchers benefit from having access to an environment that is independent of primary processes and tolerates interruptions, downtime, testing, risks, and pilot activities. These environments are referred to as learning factories [3], providing reality-conform learning environments, in which trainees can discover and test approaches or conduct experiments on technological and organisational industry-related issues [3, 9, 10]. Learning factories support the methodical modelling of effective competence development, enable feedback processes for the learner, and simultaneously open possibilities for production research. Figure 1 shows the design and embedding of the learning factory that is currently under development at the University of Twente. This figure illustrates how digital twinning (see section 2) caters for the information provisioning in the envisaged learning factory; it also shows a recursive master-apprentice relation (section 3.1) driving the integration of education and research (section 5).

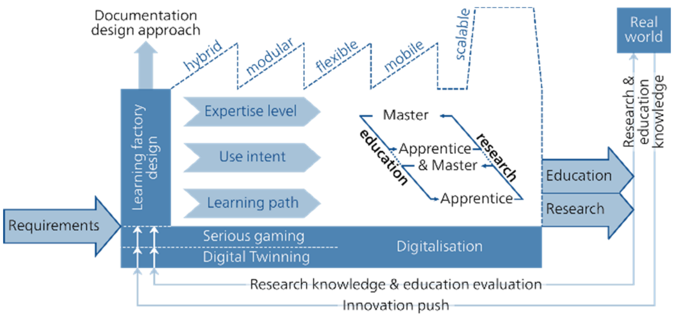

Fig. 1. Schematic overview of the apperception of the learning factory.

In a typical learning factory, the abundance of data that characterises industrial production environments does not exist. However, with the digital twinning approach, such data - as captured in PLM, ERP, or MES systems, for example – can be inferred from actual systems in industry or from models or simulations. Such simulations can follow different scenarios and situations, thus mimicking different scenarios and strategic considerations. This allows assets, machines, or systems in the learning factory to adhere to a 'digital prototype' that, for a beginning learner, imposes behaviour according to a scenario. Scenarios can stem from real-world conditions or are based on engineering models established by advanced learners or researchers. Here, uncertainty is not something to be mitigated; it rather is characteristic of integrating different stakeholders and different levels of aggregation. In a fault-tolerant manner, all stakeholders can experiment – each at their own level.

With all the information that is available, the envisaged learning factory can be accessed both physically and in virtual reality. For example, the learning factory can present alternative solutions in decision making, switch/integrate different perspectives, provide role-playing in serious gaming, contextualise process/production planning, or allow for immersion in potential future configurations of the factory. Such techniques take the learner along a learning curve that can be comprehensive, contextualised, and effective – with each technology also allowing the identification and highlighting of hurdles or omissions in the learner's ability to fathom a topic. By generalising and aggregating such meta-information, the learning factory as a whole can 'learn' from how it's used [11], enabling inherent optimisation of the learning factory [12] and its educational/didactic approaches.

3.1. Recursive master-apprentice approach

The learning factory concept focuses on education and learning, where the activities of students and staff determine the effectiveness, efficiency, and impact of the process. A traditional master-apprentice approach would have significant advantages here, as it allows for reflection on activities and decision-making, and for conveying tacit knowledge. Yet, given the attainable student-to-staff ratios, and the different fields of expertise involved in academic education, such an artisanal approach is not feasible. A contemporary interpretation of the master-apprentice approach is envisaged, which allows for differentiation in time and place of the staff, but also for an inherent quality control of the knowledge transferred, while explicitly focusing on the alignment of learning approaches, objectives and assessment [13]. This involves solutions that virtualise processes, observations, and training to overcome the simultaneity of activities and locations. This requires a sound information backbone that monitors, guides and controls what information is available to whom and in what format. To this end, digital twinning is integrated into the learning factory, as an approach to transcend rigidity by process orientation [14]. This digital twinning, together with serious gaming, gives context to both the master and the apprentice in their endeavours [4]. Additionally, the contemporary interpretation introduces a way of thinking that allows for different levels of aggregation in the learning factory. This leads to peer learning and the creation of a more realistic environment for exploration. A recursive master-apprentice approach (see figure 1) embeds students in the knowledge and insights of advanced learners and staff, allowing them to progress and council subsequent learners. This makes learning more active, and challenges learners to replicate, use, reflect on, and creatively apply the expertise they are building. Assessment in education can focus more on the formulation, development, and evaluation of knowledge and decisions, than on the reproduction of factual knowledge.

4. Daydreaming factories

Any learning factory, or more generally, any environment where learners or researchers are exposed to an industrial context, benefits from being represented by sufficiently available and realistic data and information. Physical environments can rely on the underlying information provisioning (e.g., PLM, MES) to accurately represent the actual conditions. However, as mentioned in section 1.1., the approach depicted here aims to transcend the 'as-is' situation as it may be captured by a digital twin. For that reason, the envisaged learning factory has an explicit virtual extension, that allows for immersion in alternative, or potential future realities. This allows stakeholders to interact with a 'could-be' situation (or digital prototype). However, where individual stakeholders can carve out scenarios or what-if questions that are the base for such potential futures, it would be impossible for them to generate the associated data and information in a consistent and conscientious manner. To embed scenarios or what-if questions in representations of potential futures, the 'daydreaming factories' concept [2] is applied. This concept relies on using an innovative understanding of the production environment in the form of a digitized representation of the system, based on engineering models, conducting reveries by generating multiple scenarios and gaining insights from the potential outcomes. Figure 2 shows the articulation of such a framework for the specific cases where the system is an industrial value-adding entity; thus, equating commercial manufacturing environments and learning factories.

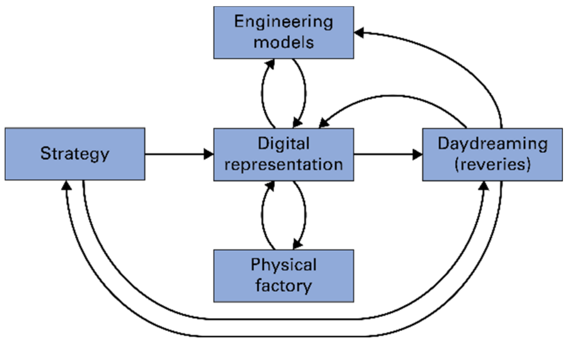

Fig. 2. Simplified framework of daydreaming factories (adapted from [2]).

The framework reasons from a digital representation of an environment that is based on the physical factory, on engineering models, or on a combination of both. This digital representation will, given the many different stakeholders involved, be subject to any prevailing (company) strategy. In the daydreaming factory, learners and researchers alike, can explore different strategies or consider alternative engineering models, by means of the reveries that explore possibilities [2]. These reveries are based on the application of scenario generation, which relies on structured randomization of variables to generate many different potential futures in a form that is suitable for research, using either analytical techniques or simulations. Daydreaming exceeds the potential of individual simulations, by using scenarios in which the value of parameters, but also the parameters themselves are subject of exploration. Applying simulation or analytical techniques to these representations yield outcomes that in the presence of human, artificial or blended cognitive ability, are transformed into foresights of what could happen in the future of the (learning) factory if the new technology is applied, the new understanding of the engineering model is correct, or the new strategy is adopted. Cogitation on the foresights yields practical measures that lead to adaptations in the underlying strategy, to improved engineering models and/or to updates to the digital representations [2]. The reveries and foresights lead to digital representations as a basis for exploring and assessing decision making in learning factories – regardless of the perspective, level of expertise, experience and role of the stakeholders involved. With that, daydreaming factories mitigate 'class differences' between stakeholders, and thus between, for example, beginning learners and researchers.

5. Integration of education and research

The recursive master-apprentice approach to learning and research uniquely integrates the two and blurs the distinction between them. This method encourages students to learn and apply new skills in the context of ongoing research projects, providing them with a valuable and realistic learning experience [4]. For example, students can use virtual or augmented reality solutions to learn about an assembly process, while the development and testing of these solutions is part of a larger research project. This allows learners to become familiar with research methods and new advances in a 'living environment' and provides researchers with a direct link to a practical and purposeful testing ground [6].

The envisaged learning factory will use a variety of integrative methods to promote engagement, motivation and creativity among learners and researchers. These methods encompass different levels of aggregation, such as teaching students about production line concepts while also researching related planning strategies and quality management. In addition, integrative methods can include different perspectives and aspects, such as using technologies like IoT sensors and automated guided vehicles (AGVs) as teaching tools, while at the same time testing and developing Industry X.0 concepts.

The learning factory acts as a pilot production plant, allowing a company to develop, test and improve production processes without disrupting primary operations or requiring excessive investment. In addition, the learning factory provides opportunities for both educational and user-oriented research, such as exploring user interfaces, maintenance practices and workplace ergonomics. By integrating education and research in this way, the learning factory creates a dynamic and immersive environment for students to learn, grow and make valuable contributions to ongoing research projects.

The envisaged learning factory will also serve as the basis for a teaching and learning community. In this community, there are no clear hierarchies or predetermined roles for students, teachers, or researchers; it is foremost intended to be an environment that stimulates knowledge transfer. With that, all participants in the learning community have comparable and equivalent roles, with advanced learners foremost having a head start over beginning learners – and researchers learning from (decision making by) even beginning learners. Yet, as beginning learners progress, they again will have an advantage over incoming novices. With that, the learning community is an amalgamation of successive generations of learners, maturing in the process as they develop into researchers or, potentially, into teachers.

6. Implementation

It goes without saying that the approach depicted here requires significant investments, innovations, and adaptations – in the educational programmes, in research projects, in machine tools and assets, but also in the overarching infrastructure. As mentioned in section 3, the University of Twente is currently defining a new learning factory. Given the increase in student numbers and research projects – as well as an initiative to overhaul some education programmes, there is currently a combination of circumstances that allows for a significant investment in a facility that will house multiple workshops, and, for example, a dedicated learning factory for production and assembly of typical 'shoebox' sized products. The whole process of manifesting this new facility spans several years. Explicitly and deliberately, the result of this trajectory is not a turnkey solution, but rather the outcome of an ongoing development cycle consisting of education and research. Therefore, several setups (from individual machines, to cells or lines to control systems) that will eventually form part of the overall facility, are currently already under development. Currently, and increasingly, these setups serve as prototypes, testbeds, commissioning setups, and as simple try-outs. By developing these setups separately (currently in different locations), while simulating and testing connectivity between them, the recursive digital twinning approach (see section 2) is an inherent feature of all developments. Furthermore, successive groups of students are – and will be - involved in the development and use of the different setups. This allows the recursive master-apprentice approach (see section 3.1) to mature and be stress-tested, in collaboration with the researchers that drive the overall development process. Hence, the recursive digital twinning and master-apprentice approach are integrated into the development, setup, and use of the production facility under development.

6.1. Implementation setup

Where the modular and recursive nature of the current setups is to be retained in the envisaged facility, the underlying way of working presents challenges in terms of, for example, shopfloor management and logistics. Such challenges are closely related to the need for flexibility and adaptability of industrial production environments. In order to respond to such challenges, the implementations of the individual setups are linked to different variants of software systems. Even more, learners and researchers work at different solutions simultaneously, for example to compare them, to use the solutions in simulations or foresights, and to come to informed decision making on how to implement or optimize systems. In this, often, learners are challenged to convert their theoretical knowledge into practicable and demonstrable software (for example, on capacity planning, process planning, scheduling, or IoT), where other stakeholder aim to assess the suitability and added value of available research/commercial software.

These systems are tested by students and researchers alike, in order to gain experience, optimize them and assess their ability to serve as instrumental tools in the overarching production facility. The systems being tested range in level of aggregation and in perspective on production environments. Where the envisaged overall facility requires significant underlying installments of, for example, PLM, ERP, MES, CAQ and various other systems, the current setups allow for testbed implementations of (parts of) such systems. Where the individual setups only cover a small part of the complexities that characterize such systems, the daydreaming factories concept (see section 4), from the outset, provides related, extrapolated, and extended information bases for simulating more complex environments, infused by simulation software like Siemens Plant Simulation or Opcenter. This also uses resource connectivity based on the OPC-UA standard to provide test-data to drive the daydreaming. At the same time, for example, Real Time Location Systems (RTLS) are being implemented, used, and evaluated – in education and research alike - as test-setups for the envisaged facility. The test setups are selected to represent different parts of the supply chain, different aspects of production and production development, and different approaches to digitization. Current setups include a measuring chamber, a robot cell, a prototype AGV, an assembly line, workbench ergonomics, and a mini-factory.

7. Implementation case study

One of the test setups is a mini-factory that uses ‘desktop equipment’ such as a Stepcraft M700 CNC mill, a Creality Ender V3 3D printer, and a Franka (pre-production) robot (see figure 3). This low-cost setup allows for flexible reconfiguration of a production cell that is the basis for a wide range of projects where education and research come together. The pragmatic prerequisite for the integration of education and research in this is the availability of all relevant data for all stakeholder perspectives involved. This is where the recursive digital twinning approach is instrumental, in addressing the different perspectives, and in providing a data and information realm at machine and at cell level. For example, AR tools such as hololenses are used to allow learners and researchers to explore their own expertise in depth, but also to experience and communicate with other perspectives. As a result, this test setup provides a learning environment for beginning learners, while advanced learners focus on aspects related to optimization, interfaces, user-interfaces, maintenance, repair

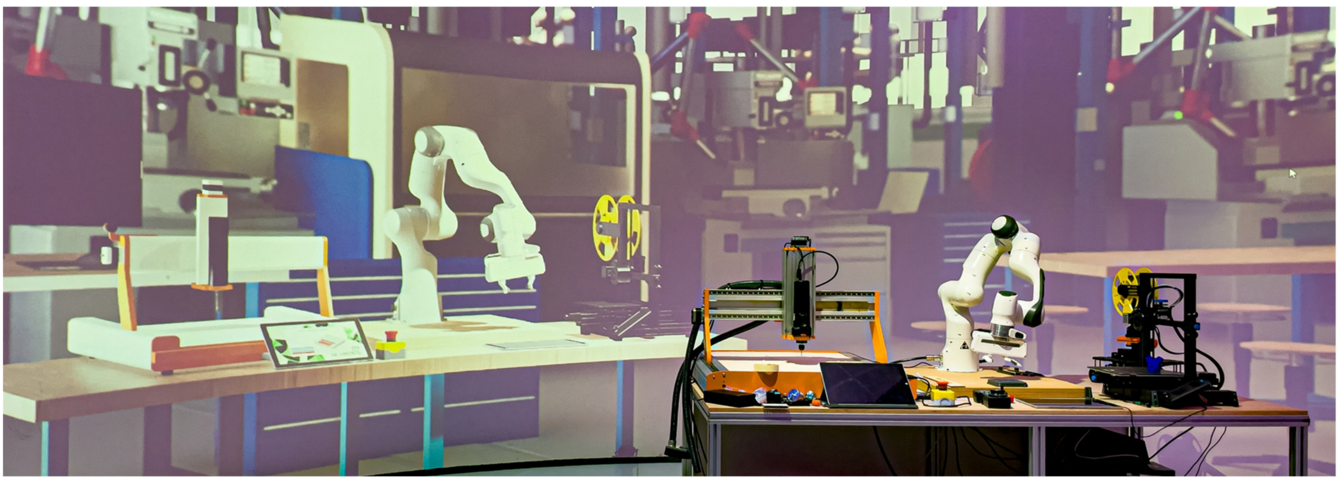

Fig. 3. Illustration of one of the test setups, together with a visualization of its digital twin in the context of the envisaged (learning) factory.

and takt time balancing. At the same time, researchers are using the same digital twin to develop interfaces with simulation software, daydreaming scenarios, and links to other setups. Currently, students and researchers are already working on specific setups, that represent clusters and viewpoints of the envisaged learning factory. Thus, they work on digital twins, that together will represent the overall learning factory. For example, existing software and protocols for controlling the mini-factory and its constituents are tested; also new software for planning the mini-factory is developed. Other students collaborate with researchers to provide protocols for virtual commissioning of the mini-factory. This virtual commissioning can lead directly to 'real' commissioning, because most resources in the test setup run software or operating systems that are identical to the software in their industrial counterparts. For example, the small robot in the test setup and the AGV are standardized on the robot operating system (ROS), which is the same set of software libraries and tools that underlies the industry scale robots in the learning factory.

Thus, most of the setups have three manifestations in the production facility: a prototype setup, a virtual counterpart, and an industrial scale setup. This provides an interchangeability that directly supports the intended master-apprentice relation and the integration of education and research embedded in the existence of digital twins of the physical setups and a digital prototype for the daydreaming extension or contexts. For example, the background image in figure 3 shows the current state of the layout of a part of the envisaged learning factory, replicating the physical mini-factory in front of it as an integral component in this factory – either as a digital master or digital prototype in the digital twinning approach. At the same time, the background lay-out can provide a configurable virtual context for the mini-factory. Thus, the amalgamation of physical and virtual entities provides the desired safe environment for learners and researchers. In addition, the setup exploits the capabilities of recursive digital twinning, in mimicking the individual resources in digital twins and the mini-factory in a digital twin, which subsequently becomes part of a (currently virtual) learning factory digital twin.

As a result, learners and researchers currently working on the setups, such as developing worker-safety enhancements to the mini-factory, have been observed to seamlessly switch between measurements in the physical mini-factory and simulations in its virtual counterpart. They also incorporate scenarios and daydreaming foresights into their decision-making process to design experiments, and to quickly test proposed solutions in the digital prototype of a production environment that does not yet exist.

8. Concluding remarks

The integration of education and research is a key aspect of the envisaged learning factory concept. The recursive master-apprentice approach to learning and research blurs the distinction between the two, providing learners with a valuable and realistic learning experience – and researchers with a valuable and realistic learning living laboratory. But this is only possible if learners and researchers can interact with the learning factory and all its components in a purposeful manner. In various test setups, it is shown that the recursive digital twinning approach enables this; it is demonstrated that it provides an adequate basis for the development of working methods and, e.g., software tools. At the same time, the recursive nature of the digital twinning approach has proven to be instrumental in linking different machine tools in a cell and different cells in the overall (currently virtual) factory. Furthermore, the digital twinning approach allows learners and researchers to work together on different parts of the supply chain, different aspects of production, and different approaches to digitalization. The learners and researchers are each other's counterparts and co-workers, providing data and information, experience, but also in challenging and testing each other's proposed solutions from different perspectives.

The current portfolio of test setups will continue to expand and evolve – individual setups are optimized, made more modular and flexible – also, more setups will be developed, until the individual models merge into the envisaged learning factory. Future research foremost focuses on evolving, testing and scaling-up the recursive digital twinning approach. There will also be a significant increase in attention to the implementation of software solutions for managing the environment (e.g., PLM and ERP), and the simulation of the behavior of such software in virtual environments, whether driven by analyses, scenarios, or daydreaming.

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