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Digital Twin training concept based on miniature demonstration factories

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Abstract

This paper presents a training concept, which aims at conveying the concept of a Digital Twin (DT) to different target groups based on two miniature learning factories. Enabled by recent advances in information technology, such as Internet of Things (IoT) and Cloud-based Manufacturing (CBM), DTs have become a promising approach to cope with the challenges of modern production systems. Unfortunately, the complexity of the concept as well as unfamiliarity with the potential benefits prevent many companies from implementing DTs. The presented approach aims at making the abstract concept of a DT tangible for industry executives and practitioners as well as university students by allowing them to experience working with DTs interactively in learning factory environments and simulated production facilities. The paper outlines the structure and components of the courses, the different target groups and learning objectives and the learning environments that they are based on. The resulting modular training concept is matched with the requirement profiles and two different learning factory facilities or equipment. The preliminary evaluation results indicate the principal suitability of the target group centered approach as well as the benefits of integrating it in simulated production facilities and equipment.

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Keywords: learning factories; digital twin; miniature demonstration factories; training concept

1. Introduction

Recent advances in information and communication technology have paved the way for Cyber-Physical Systems (CPS) and Digital Twins (DT), which help coping with challenges such as mass customization and competitive markets [1]. However, production companies are still far from exploiting the full potential of these technologies. Aside from organizational and technical challenges, e.g. data availability, unfamiliarity with the capabilities requirements, complexity and impact of DTs is a major obstacle to widespread implementation [2]. Moreover, DT implementation requires new technical and interdisciplinary skills [3]. While DT implementations is a broad field of research, educational solutions are still insufficient. In the field of teaching concepts for applied concepts in production, learning factories have been established as a powerful tool to support the conversion of theoretical knowledge into practical understanding. Thus, this paper aims at addressing the need for efficient DT training by integrating elements of learning factory concepts. Since the need for DT training concerns stakeholders of different backgrounds and skill levels, requiring a range of content, the goal of this paper is to develop a modular approach, which can be customized to their specific learning objectives. The proposed training concept is based on two learning factories within the framework of an international cooperation between Austria and Hungary [4]. The article is structured as follows: The second section covers definitions, existing concepts of DTs and learning

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factories in a DT context. The third section presents the developed modular training concept and the integration of learning factory elements. The fourth section introduces preliminary results from the evaluation of the concept, including participant's feedback. The closing fifth section discusses the findings and gives a research outlook.

2. Basics and related work

There is not one single accepted DT definition in the field of manufacturing systems, however, since the concept involves an interaction of a real-world system with a digital representation, the literature provides a nomenclature for three different levels of information-exchange between both components: *digital model* (simulation model without ongoing data-link to the physical system), *digital shadow* (one-way data link from physical to virtual system, which provides real-time monitoring functionality), and *digital twin* (two-way data link and featuring an optimization functionality that provides ongoing optimized planning and control for the production processes and equipment) [1]. Although DTs in the field of optimizing production operations are far from an established industry practice, there are a number of sophisticated DT implementations, e.g. for simulation-based optimization of production planning [5] or for reconfiguration of robotic work cells [6] – these kinds of demonstrator implementations can serve as references, which the training concept should help proliferate in the industry.

The technical requirements of DTs are thoroughly examined in research [7], however the there is a significant gap between academia and practice [8]. Industry 4.0 readiness and qualification models are aiming to determine the missing competences and technologies for a given company [9]. The lack of DT specific knowledge and absence of teaching courses are one of the highlighted reasons for the non-implementation, along with the lack of technology solutions in the factory. Although qualification measures concerning Industry 4.0 technologies are gaining importance, such training possibilities are currently rare [10,11]. Since DTs are still not well established in industry, learning factories play an important role for a common understanding between academia and industry [12]. To provide an opportunity to learn the DT modelling skill, it is necessary to present the state-of-the-art procedures and considerations [13].

The intended learning concept of this paper, focusing on the environment and tools used to actively transfer domain specific knowledge and less on the passive information intake aligns well with the learning factory approach [14]. The lack of digital learning activities in learning factories are detailed in [15], regarding DT and also Augmented and Virtual Reality (XR) technologies. The aLF-framework provides a step-by-step guide to design training courses for industrial demands [16]. SEPT Learning Factory is a university-based facility with a strong educational embeddedness, which provides several good practices and criteria for teaching courses [17]. A good example for the use of gamification in a lean and digitalized production training course is detailed in [18]. D3LF@RACE learning factory focuses on the "digital triplet" concept, which incorporates the intelligent human activity as a third part together with the virtual and physical world [19]. Digital Factory Vorarlberg is a similar approach, which focuses on the data security and software solutions of DT on a cloud-based basis [20]. Implementation of a DT application can be challenging without exact steps and guidelines; however, a Brazilian learning factory presents such on an easy to understand digitalized skateboard [21]. Although these learning factories demonstrate the use of DTs, they do not offer dedicated teaching and training concepts. [22] presents a learning concept which provides a comparison between a DT and a Value Stream Mapping solution. However, no training approach with learning factory elements could be found that covers learning objectives from comprehensive understanding to teaching the skills needed to implement DTs.

3. Training concept development

3.1. Target groups & learning objectives

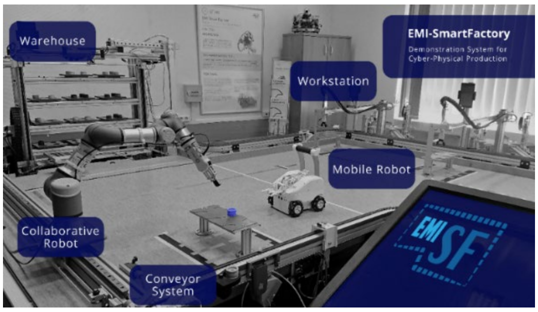
The training concept was developed based on requirements-profiles identified though expert interviews with three backgrounds: industry experts in discrete manufacturing, responsible for digitalization as well as production planning and control (PPC), instructors for PPC courses from the applied research institution Fraunhofer Austria Research as well as teaching experts at the universities of Széchenyi István University in Győr, Hungary, and TU Wien in Austria. Four major target groups were identified, according to their required level of expertise. To provide an effective knowledge transfer, four course levels matching the target groups have been defined: Two academic or teaching oriented levels, i.) Entry and ii.) Advanced, plus two enterprise-practice oriented levels, iii.) Executive and Manager (E&M) and iv.) Designer and Developer (D&D).

Entry level participants can be undergraduate students and interested members of the public. The course goal is to familiarize the trainees with the topics of PPC and digitalization in industrial environments as well as developing an intuitive understanding of the interaction of the physical and virtual elements. The Advanced level focuses on a more technical aspect of DTs and production control and is aimed primarily at master's students in mechanical and industrial engineering at universities and technical colleges. The course aims to provide a comprehensive knowledge of methodologies, programming and working with DTs. Next is the E&M level course, aimed at individuals in decision-making requirements positions in companies e.g., production or site managers as well as chief technology officers – the course sets as a goal to provide a solid general and holistic understanding of the prerequisites, capabilities, limitations and characteristics of DT applications and the underlying technology for production planning and control. Furthermore, the benefits and costs are highlighted for an informed implementation/management decision-making regarding DTs. Finally, the D&D level lessons cater to technical industry experts, such as senior production engineers and developers – here, the goal is to provide in-depth knowledge required for the design, implementation, and integration of existing and new DT solutions. The underlying technologies as well as the software and hardware components according to current standards are the main elements of the D&D course and hands-on programing assignments aim to qualify the participants for independent implementations in practice.

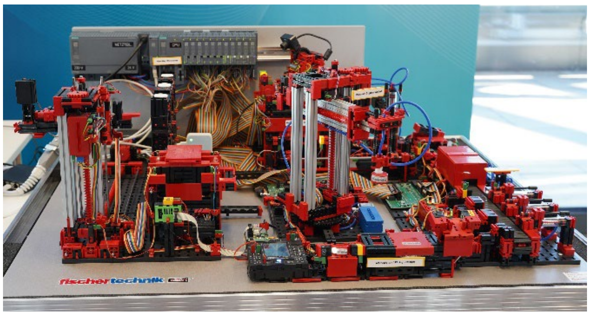
3.2. Introduction of the research environments

To enable an intuitive hands-on learning experience, the training concept is integrated with a learning factory element. There are two such learning facilities designed around aspects of a digitalized production – see Fig. 1.

The first is the EMI-SmartFactory, a twenty square meter compact research and demonstration facility for cyber-physical production systems related topics, such as DTs, Internet of Things and the OPC UA standard. This model factory was originally designed for educational courses in production control and informatics. The main components are a four-storey high warehouse, four identical multi-purpose workstations, a conveyor system connecting all elements of the system and an autonomous mobile robot fleet, which are detailed in [23]. The service-oriented execution system supports the in-depth analysis of every process during the exemplary runs. Since the EMI-SmartFactory uses industrial-grade equipment and features a complex production process, it supports teaching skills directly relatable to industry applications, e.g. programming field controllers up to web-services.



a. EMI-SmartFactory



b. MIND.Factory

Fig. 1. Learning facilities.

The second is the Miniature Digital Factory (MIND.Factory), based on the hardware components of the "Training Factory Industry 4.0" by Fischertechnik. On a base area of less than a square meter, miniature cylindric workpieces are transported to and from a warehouse and different workstations. The production steps as well as the transport of the workpieces through a vacuum gripper robot are fully automatic and controlled by an industrial programmable logic controller (PLC). For this setup, a DT optimizing production scheduling was developed. The DT features a simulation-based optimization. Orders with due dates and product-specific energy consumption on the machines are processed and a multi-criteria optimal schedule is compiled with the help of metaheuristics, i.e. customized genetic algorithms. Sensors and data input from the PLC provide the DT with near-real-time status information, ensuring the simulation is always updated and new optimized plans are created constantly, e.g. to react to machine breakdowns or other disturbances, and executed via the PLC. The MIND.Factory is compact and packs into an industrial aluminum case that fits into a normal station wagon. Due to the abstraction, simplification and miniaturization, the MIND.Factory enables easy understanding of general principles and can be used location independent and with very little effort.

3.3. Training modules

Since all training courses are centered around aspects of the DT, most of which are to a degree relevant to all four target groups and corresponding course levels, the courses should be based on modules that cover major aspects of DTs. These modules are then combined to build the course-level specific programs. Most of them are designed to have a basic and an in-depth version. The basic courses are more concept oriented in contrast to the implementation-focused in-depth lessons. The modules and their contents are detailed in Table 1:

Table 1: Contents of the course modules

Modules		Content		Duration in hours	
#	Name	basic	in-depth	*basic*	*in-depth*
1	General introduction to Digital Twins	differences between the concepts digital model, digital shadow and DT	possible applications and benefits of the three concepts	0,5	0,5
2	General introduction to Production Systems and Management	basic understanding of the structure, processes, and objectives in modern production environments	-	1	-
3	Technical introduction to Hardware Components and Software Solutions	highlighting specific approaches, benefits and limitations of relevant control electronics and programming options	providing necessary know-how to develop and implement relevant hardware components and software	2	4
4	Capabilities and Limitations of Digital Twins	performing production planning tasks with the help of a DT	performing production planning tasks with different levels of DT integration	2	4
5	Production Planning, Scheduling, Simulation and Optimization	basics of production planning and optimization strategies and methods	exercises with greater scope than in the basic module and concrete case studies	2	4
6	Programming in Industry 4.0	overview of the industrial control hierarchy and the necessary development approaches	specific tasks to implement industrial control structures from PLC statement lists to MES execution routing	3	6
7	Demonstration	demonstration of the functions of the implemented DT and experiencing the system behaviour intuitively	demonstration of the functions of different levels of DT integration	0,5	1-2

While the Modules 1, 2 and 5 are mostly independent from the learning factories, the other modules aim to leverage the possibilities of an interactive learning environment. In Module 3 most of the discussed hardware components like PLCs or smart sensor networks along with their programming options can be experimented with. Module 4 enables the participants to reflect on the capabilities and limitations of DT solutions through the experience they gained by performing production planning tasks with the help of the DTs of the learning factories. In these tasks the participants need to find good production planning solutions in the face of conflicting part goals (e.g. lead-time and energy-efficiency) and short reaction times. For example, connecting the digital factory model to status sensors and automatic planning optimization improves the system's reactivity, resulting in visible KPI improvements in the physical learning environments. This makes the advantages of the concept easily understandable to the participants. In the in-depth version it is moreover possible to experiment with different levels of DT integration so that the participants can assess which level would be suitable for their real-life problems. In Module 6 the participants can gain practical experience by performing the implementation tasks in the learning factories. Module 7 shows the functions of different DT implementations of the learning factories. Although these demonstrations are an integral part of most modules, they can also be used as standalone module, e.g. for initial briefings and presentations, both in an academic/teaching and industry context. It is also possible to present the DT of the learning factory which is not physically present virtually to demonstrate another possible integration of a DT in this module.

4. Results & Preliminary Evaluation

The following section presents the resulting training concept, combining the target groups and corresponding course levels, with the modules that are assigned to the levels and finally indicating, which of the learning facilities is most suited for each of the level-module combinations. Table 1 provides an overview of the course structure. In principle, all courses and their modules could be conducted with both learning facilities, but for most modules there are clear advantages for one or the other equipment.

With the MIND.Factory concepts of production management can easily be made tangible, as the production process is simple and the effects of the implemented concepts can be seen immediately. Yet, these simplifications limit the possibilities to portray problems of real factories. Hence, the MIND.Factory is better suited to convey concepts on a strategic level than to gain operational experience which can directly be transferred into practice. Thus, the implemented use-cases aim at showing the idea and the advantages of a DT, rather than teaching the use of an application. Another advantage of the MIND.Factory is its transportability. The factory is designed to fit into a case and can be transported and build up practically anywhere. Thus, it can be used for trainings and demonstrations in the accustomed environment of the participants. The Executive and Manager level is best suited for the MIND.Factory, where the participants can experience the benefits and limitations of a DT without the need for a deep understanding of the technical components. The EMI-SmartFactory however enables the participants to gain a deeper experience with building and working with a DT, which is why it is ideal for most of the Designer and Developer level modules.

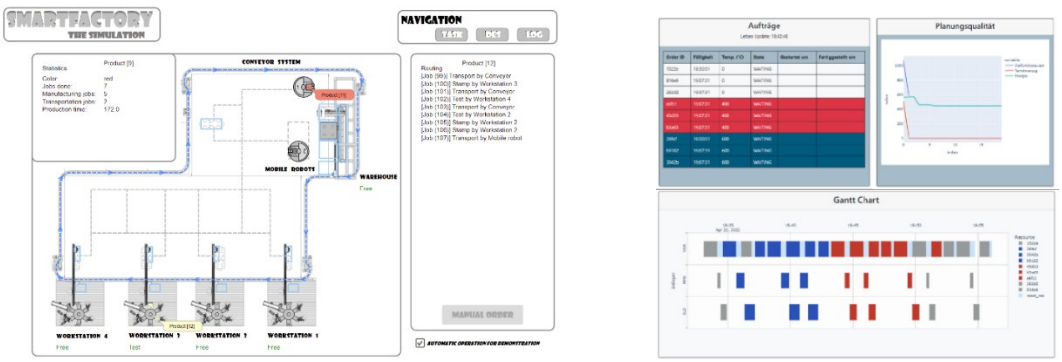
Table 2: Modules and facilities of the different course levels

Modules		Levels				Facilities	
		teaching/academia		enterprise/practice			
#	Name	Entry	Advanced	E&M*	D&D**	EMI-SmartFactory	MIND.Factory
1	General introduction to Digital Twins	basic	in-depth	basic	in-depth	in-depth	basic
2	General introduction to Production Systems and Management	basic	basic	basic	basic	basic	basic
3	Technical introduction to Hardware Components and Software Solutions	none	basic	none	in-depth	in-depth	basic
4	Capabilities and Limitations of Digital Twins	none	none	in-depth	basic	basic	in-depth
5	Production Planning, Scheduling, Simulation and Optimization	none	basic	basic	in-depth	in-depth	basic
6	Programming in Industry 4.0	none	basic	none	in-depth	in-depth	basic
7	Demonstration	basic	basic	basic	in-depth	in-depth	basic

*Executive and Manager; **Designer and Developer

Concerning the evaluation of the developed training, it must be noted, that the following are preliminary findings, since the entire course-program has just been finalized and has not yet been executed in its entirety. The EMI-SmartFactory has been part of university courses for several years with text-based feedback from around five hundred engineering students, both from online and in-person lab practice, which varies from one to one and a half hours, showing that the courses are relevant and interesting (i.e. motivating) for them. Many improvement suggestions are being submitted annually, which are considered in the development of the facility and the courses. The general criticism expressed by the students was the lack of transparency due to the system complexity and the high-level of abstraction required to match their previous experiences regarding production facilities, because of the condensed size. Although both points lead to contradicting goals (i.e. reducing complexity would likely require more abstraction), the latter is an indication that the might be a need for a third learning factory environment, which could be implemented with a bigger facility or, more economically, with industry related assignments, designed in cooperation with an industrial partner at their manufacturing plant.

The MIND.Factory has been used to demonstrate, how a DT can be applied to support production planning at events for industry stakeholders as well as public events. It has proven to be capable of triggering interest in the participants through its playful appearance. Through its simple design it is possible to explain and show the concept of a DT in only a few minutes. However, it was difficult to generate an understanding of the interaction of the different components through mere demonstration.



a. EMI-SmartFactory b. MIND.Factory

Fig. 2. DTs of learning facilities.

5. Discussion and Outlook

The presented training concept aims to contribute an example for the sensible design of hands-on learning opportunities to address the current lack of knowledge concerning benefits of DTs and how to implement them. The stakeholder-oriented, modular approach and the systematic integration of different learning facilities is also intended as a proposal for a design principle of similar training concepts for specialized use cases. We could show that different learning environments are best suited to support specific learning objectives. E.g., while the EMI-SmartFactory is better suited for exploring the technical details of DTs in longer, more realistic trainings, the MIND.Factory is convenient for trainings for non-technical experts due to its simple setup and transportability. Concerning a more general interpretation of the results thus far, we suggest seeing the two factory examples for certain types of learning facilities – i.e., equipment and systems with this kind of characteristics are especially fitting for that kind of intended learning outcome and the targeted use of fitting learning facilities can improve the teaching and learning experience. Although the two factories have already been used for training and demonstration purposes with positive feedback, the presented learning concept has yet to be thoroughly tested and evaluated, the results of which will be presented in an upcoming publication. This process will also involve the adaptation of the concept, and the learning facilities, which are a constant work in progress, according to feedback and teaching experience, as well as integrating new DT challenges, such as energy efficiency and flexibility, for which DTs will likely be a major facilitator [24].

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