An Adaptive Learning Environment for Industry 4.0 Competencies Based on a Learning Factory and Its Immersive Digital Twin

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Abstract: Technological advancements and the interdisciplinary nature of modern engineering projects are driving forces behind the evolution of engineering skills today. Educational institutions are responding to the demand for new skills through various initiatives, one notable example being the implementation of learning factories. These facilities serve as invaluable resources for hands-on, practice-oriented learning, particularly in the context of Industry 4.0. This publication outlines an innovative teaching concept and the implementation of an adaptive and immersive learning environment tailored for Industry 4.0 education. Central to this environment is a cost-effective learning factory model complemented by its immersive digital twin, accessible on desktop PCs or immersive hardware. The virtual learning environment comprises diverse teaching modules covering advanced engineering topics such as agile production, industrial Internet of Things, automation, machine learning and autonomous guided vehicles. The integration of a physical learning factory with its immersive digital counterpart allows for the playful exploration of additional relevant topics such as digital twins, virtual commissioning and extended reality. The adaptability of this hybrid learning environment enables educators to customize teaching scenarios and adjust content and difficulty levels to suit various learner groups. Furthermore, it accommodates a wide range of teaching methods and classroom setups, offering a versatile educational experience.

1 INTRODUCTION

As technology advancements revolutionize traditional production methods and reshape the operational landscape for businesses, they present a myriad of opportunities and challenges. Navigating this transformation in future factories inevitably alters the competencies and skill sets required of engineering professionals. Many educational institutions are revising their curriculum to incorporate emerging technologies and skills relevant to the future job market. There is a growing recognition of the importance of lifelong learning in staying competitive within the workforce. Many organizations are offering continuous learning opportunities for their employees. In addition to technical skills, there is a growing emphasis on the importance of soft skills such as communication, critical thinking, creativity, and adaptability. Furthermore, advances in learning technologies, such as virtual reality, gamification, and adaptive learning platforms, are being leveraged to create engaging and effective training programs. These technologies enhance the learning experience and make education more accessible to diverse learners.

Learning factories are an important educational resource, particularly in the field of engineering education. Tangible learning factories are designed to represent industrial environments as realistically as possible. In recent years, they have been increasingly used to illustrate the changes associated with Industry 4.0 and to specifically promote the learning of the necessary skills. In learning factories, inter-

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linked workplace and machine chains are available for various phases of the production process. Learners can gain practical experience with modern plant modules and even with product development methods (Abele et al., 2017). Learning factories integrate teaching, training, and research within a realistic production environment, employing didactic models for the conveyance and reflection of learning content. Defined in a narrower sense, a learning factory is an educational setting characterised by authentic processes that include multiple stations and cover both technical and organisational aspects. This adaptable environment mirrors a real value chain where a physical product is manufactured. The pedagogical concept behind a learning factory encompasses formal, informal, and non-formal learning, facilitated through the direct actions of trainees in an on-site learning approach (Abele et al., 2019).

One way of making the most of the learning factory concept is to offer digital or virtual learning environments. Digital and virtual learning factories exist at various educational institutions, including universities, companies and, in some cases, vocational schools. They are used for training in similar areas to physical learning factories. At the same time, they function independently of location and do not involve the large financial outlay of a physical learning factory. They are therefore considered an important strategic tool for implementing education in the field of manufacturing (Abele et al., 2017). Learning in virtual environments is being used more and more frequently in various scientific disciplines due its benefits (Häfner, 2020). In engineering, particularly, the integration of virtual learning environments as a didactic tool is now widely recognized (Häfner, 2021). A virtual learning factory promotes the learning of advanced manufacturing concepts by combining virtual objects with hands-on activities and providing learners with a motivating learning experience (Aqlan et al., 2021). Learners can experience a collaborative and immersive learning environment in a realistic simulation. Moreover, diverse learning scenarios can be effectively addressed by adjusting and incorporating additional objects as needed.

A review by Reining and Kauffeld (2022) summarised the empirical evidence on learning outcomes and skills development in learning factories (Reining and Kauffeld, 2022). A total of 22 studies were included, 16 of which were conducted in physical learning factories and three in virtual learning factories. Three further studies combined physical and virtual learning factories. The interventions evaluated included continuing education, higher education programmes and vocational training courses, mostly on topics such as lean, agility, Industry 4.0 and product or software development. All 22 studies reported an increase in participants' knowledge or skills following the learning factory interventions. Self-assessment questionnaires showed that between 47 and 100 percent of participants felt that their knowledge or understanding had increased significantly following the interventions. Knowledge tests, practical applications, interviews, and observations also showed increases in knowledge and skills. Skills, including technical, methodological, social and personal skills, were reported to have improved as a result of the learning factory experience. Looking at the three purely virtual and the three hybrid learning factories in terms of learning outcomes, they appear to be just as effective as the physical learning factories in terms of learning outcomes.

The proposed adaptive Virtual Learning Platform (VLP) in this publication leverages the Agile Production Simulation, a small-scale learning factory offered by the fischertechnik company. It incorporates an immersive digital twin, expanding upon it to offer additional educational content, resulting in a comprehensive, flexible, and expandable learning environment. The VLP can be deployed on different immersive hardware such as VR headset or CAVE, facilitating its utilization in a hybrid fashion. In the following sections, the authors describe current developments in the area of digital learning factories (section 2), the teaching concept (section 3), as well as its implementation (refer to section 4). Furthermore, a comprehensive evaluation concept is proposed in section 5.

2 RELATED WORKS

Various examples of training approaches using digital twins and virtual production environments can be identified in the literature.

The digital twin learning factory, as presented by Algeddawy et al. (2020), comprises a 1:1 scaled environment featuring various material handling modules, including an automatic storage and retrieval system, a robotic handling with vision module, a robotic pick-and-place and rotating storage module, and a robotic assembly module with a SCARA robot. Constructed using a combination of open-source and low-cost digital components, this digital twin utilizes tools such as RoboDK for 3D simulation, CODESYS for automation control programming, and Modbus and OPC UA for communication, along with Python for scripting. The model for creating the digital twin progresses through three stages, focusing on the connection to the physical twin and data processing methodologies

(Al-Geddawy, 2020).

A similar approach combining real learning factory, and its digital twin is followed by (Rasovska et al., 2022), but is advanced by a virtual reality (VR) factory model. It features two reconfigurable production lines, each comprising five assembly stations. The learning factory is equipped with MES software developed in-house, as well as ERP systems. Additionally, it utilizes flow simulation software, along with a metrology laboratory. Six ergonomics equipment, including various types of exoskeletons, and logistics equipment and line-side supermarkets are also incorporated. The developed system facilitates comprehensive practical training in industrial engineering and Lean manufacturing. Practical training is provided within Bachelor's and Master's degree programs, available in both initial and continuing education formats (Rasovska et al., 2022).

Aqlan et al, (2021) discuss the development of a virtual learning factory that represents manual and automated processes such as welding and 3D printing, including a multiplayer VR environment for toy car assembly and a car manufacturing simulation with an interactive avatar (Aqlan et al., 2021).

Sibanda and colleagues (2023) developed a VR application for lathe training, consisting of a digital content module and a game engine to teach lathe operation in a realistic way (Sibanda et al., 2023). Another concept for learning factory, based on a CNC lathe machine and its virtual representation was developed by Mourtzis et al. (2021), centered on the teaching and implementation of a Teaching Factory Network (Mourtzis et al., 2021).

A further paper explores the digitalization and incorporation of Industry 4.0 technologies within production and logistics systems, focusing on their application in contemporary teaching and learning environments utilizing the fischertechnik Learning Factory 4.0 (Behrendt et al., 2022).

As seen in the examples above, many publications promote manufacturing education using learning factories through immersive experiences (Rasovska et al., 2022; Behrendt et al., 2022; Aqlan et al., 2021; Sibanda et al., 2023; Mourtzis et al., 2021). Many of these learning factories replicate 1:1 scale machines found in production facilities, boasting high costs and complexity, and are primarily utilized for higher education purposes. While much of the literature focuses on the implementation of digital or virtual twins, there is a notable gap in discussions regarding teaching methods, didactic approaches, or comprehensive evaluation, except for the evaluation conducted by (Rasovska et al., 2022).

The novelty of our work lies in utilizing a small-scale, cost-effective factory model that offers exceptional flexibility and expandability while demonstrating agile production simulations. The primary contribution is the development of an adaptive teaching concept, manifested as a virtual learning platform, consisting of both digital and virtual twins. In addition, our didactic model accommodates highly diverse target groups and provides educators with a flexible toolset to adapt their courses to various teaching setups.

3 TEACHING CONCEPT

In this chapter, we delve into the innovative teaching concept designed to harness the synergies between physical and digital learning environments and to enable an immersive educational experience. To empower educators in utilizing this hybrid learning factory, a virtual learning platform was developed. It builds upon the immersive digital twin of the "Agile Production Simulation," providing guidance through Industry 4.0 topics and enabling educators to greatly benefit from its adaptive approach. It enables teachers to work more efficiently, granting them the flexibility to adjust learning content and teaching scenarios as needed for specific target groups. Learners have the opportunity to independently explore theoretical fundamentals in an engaging manner, and subsequently tackle more complex tasks with the guidance of the teacher. This approach enables the use of modern teaching methods such as the flipped classroom and blended learning. Educators gain time and flexibility to focus their attention more on the individual needs of the students and optimally support the learning process. This changes the teacher's role from pure knowledge provider to expert moderator, who flexibly guides the learning process. The virtual learning environment offers additional benefits, as learners can experiment in the digital realm without concerns about damaging real-world equipment. In a traditional vocational learning setting, students gain practical experience directly on machines in the shop floor. However, this often requires halting production, resulting in idle workers and potential downtime for machines and factories. Immersive digital twins provide an effective alternative.

3.1 Competences

The learning platform comprises diverse teaching modules covering advanced engineering topics such as agile production, industrial Internet of Things, automation, machine learning, autonomous guided vehicles, robotics and more. The integration of a physical learning factory with its immersive digital counterpart allows for the playful exploration of additional relevant topics such as digital twins, virtual commissioning, extended reality, as well as digital skills (as depicted in figure 1). With the help of production process modelling and analysis tools, students gain an overview of the relationships and interactions between different elements and processes in the factory environment, which increases understanding of the totality of processes and procedures. The learning environment is divided in learning modules. Each learning module includes a theoretical section, practical tasks, reflective questions, and multiple-choice assessments. The practical tasks in this learning modules are categorized based on whether they can be completed solely in the virtual or physical environment, as well as those that benefit from a hybrid approach, combining elements of both. By integrating the adaptive learning environment with appropriate teaching methods, it becomes possible to cultivate not only technological and industry-specific skills but also essential digital and cross-disciplinary competencies.

At the beginning of the VLP development, three competence levels were defined for the learners: Understand, Apply and Improve. It is important to emphasize that these three levels have different characteristics, which should not be interpreted in terms of Bloom's taxonomy of learning objectives (Forehand, 2010). Rather, the target perspectives - and thus learning levels - identified by Windelband et al. (2023) specifically in the context of vocational learning factories are used as a rough guidance for the orientation of the individual learning levels of the VLP (Windelband et al., 2023). For each of the three levels, these describe specific problem-oriented questions in the context of vocational learning factories.

Level 1 - Understand. This target perspective focuses on providing an initial overview of knowledge and skills relating to Industry 4.0 and artificial intelligence (AI). Learners are enabled to understand and comprehend facts, circumstances and contexts.

Level 2 - Apply. This perspective serves to deepen the competencies for the use and selection of suitable methods and professional actions. Professional skills are taught that are necessary to be able to act competently in the operational environment in the field of Industry 4.0. Learners are enabled to transfer and apply what they have learned to other situations.

Level 3 - Improve. At this level, an expert understanding of the specific professional challenges, necessary for tasks such as optimizing and maintaining systems within the realm of Industry 4.0, is provided.

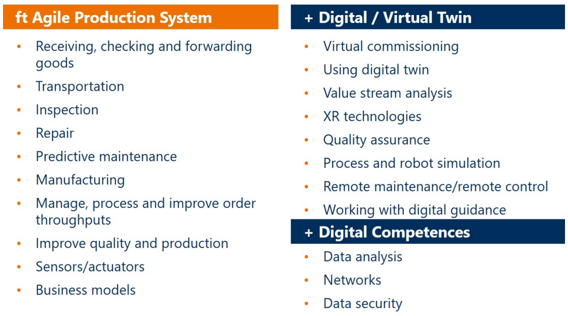

Figure 1: Expansion of the acquired skills through digital twins and Virtual Reality (left).

This level is therefore aimed at learners who have already reached level 2 and should now be able to act at higher levels and provide concrete assistance. This includes making comprehensive generalizations and finding new solutions, as well as weighing up these alternatives, evaluating them according to self-imposed criteria and making competent decisions.

All three target perspectives and learning levels differ from one another in terms of their objectives, target group and didactic implementation. Nevertheless, the boundaries between them can be fluid.

3.2 Target Group

The teaching concept caters to a diverse target audience characterized by significant heterogeneity, interdisciplinary specialization, varying age ranges, and diverse cultural backgrounds. Furthermore, it encompasses a range of educational institutions such as high schools, vocational schools, universities, as well as intercompany training and further vocational qualification.

One of the parameters used to adjust the learning environment is the learning level. The three learning levels outlined in section 3.1 target various aspects of vocational training (Windelband et al., 2023). "Understanding" serves as a fundamental stage, particularly beneficial for learners with limited prior knowledge, such as trainees in the metal and electrical industry. In this context, the VLP acts as a valuable introductory tool during vocational school lessons, offering an initial grasp of individual system components and their interplay within the broader system. This foundational module also holds potential as a primer for university students pursuing technical degrees (e.g., engineering programs). Additionally, it could cater to employees in production and logistics sectors, providing non-technical personnel (e.g., from commercial or human resources backgrounds) with an overview of Industry 4.0's technical processes.

The ”Apply” level, the second stage, is designed for proficient learners with prior training in metal and electrical professions. At this stage, the objective is to enhance skills, allowing learners to utilize their existing knowledge in new situations. For example, tasks previously focused on professional applications may evolve into tasks within the context of Industry 4.0, like repair and maintenance activities.

The third level, ”Improving,” primarily targets academic professionals such as engineers. Within Industry 4.0 systems, their roles involve process analysis, evaluation, and optimization. For this group, the VLP functions as an intermediate training tool, aiding in the comprehension and practical application of essential aspects of their professional responsibilities.

As a result, the VLP is versatile and can be used for a wide range of target groups and prior knowledge across the entire spectrum of vocational training.

3.3 Teaching Methods and Setups

The developed Virtual Learning Platform can be utilized with a wide array of teaching methods. Here, we will illustrate only some examples. The main goal of this platform is to reduce frontal teaching or augment it by active learning approaches such as practical exercises, group work or project-based learning, as well as novel teaching methods such as flipped classroom or blended learning. The use of the learning factory digital twin and VR learning environment opens up further possibilities for simulation as a teaching method. Learners could run through complex production processes in a virtual environment, simulate scenarios with different variables and analyze the results in real time. They could also specifically investigate errors or problems in a safe environment and develop solutions. Simulations as a teaching method promote critical thinking, problem-solving skills and an experimental approach among learners. They empower learners to apply theoretical concepts in practical scenarios and understand the consequences of their decisions. The VLP also allows an explorative approach, promoting self-directed learning. Learners can freely explore the virtual factory and discover different aspects of Industry 4.0 technologies and processes. This encourages curiosity and supports independent learning, as learners can explore different scenarios and application areas at their own pace.

Regardless of the teaching methods employed, the Virtual Learning Platform can be utilized in various teaching setups. Depending on the number of students and available facilities, instructors can conduct classes in traditional classrooms, computer pools, or laboratories equipped with virtual reality technology where the tangible learning factory is located. The software architecture and VR engine support the use of different immersive hardware devices such as CAVE, Powerwall, or VR headsets. Additionally, educators can leverage immersive collaboration mode for teaching. They have the flexibility to switch between the physical and virtual learning factories, particularly for topics like virtual commissioning, where processes are configured in the virtual environment and observed both virtually and in the real world.

3.4 Evaluation and Assessment Criteria

The virtual learning platform utilizes dedicated multiple-choice questions for each learning module, tailored to its specific topic. Additionally, the platform suggests questions following each task, enabling teachers to initiate discussions, foster reflection, or facilitate the transfer of learning from the simulated factory environment to real-world production settings. Furthermore, the assessment of performance and achievements within the framework of this teaching concept can be further enhanced through established evaluation criteria. One assessment method can be project-oriented work. In this case, both the individual performance standards and the expected results are taken into account in order to ensure fair assessment. The tasks and assessment criteria may vary depending on the target group and may require minor adjustments. For example, in dual study programs, the focus may be on direct applications of the technologies learned in a corporate context. For vocational schools, precise descriptions of fictitious use cases (detailed presentation of the solution space), the problems to be solved, and the solution approaches are of greater importance.

3.5 Enhancement with Gamification Elements

The virtual learning platform can be enhanced through gamification, immersing students in situational learning scenarios where they, for instance, inherit a factory. The objective is to transition it from conventional production methods to modern, flexible practices. Players must manage order fulfillment, deciding which orders to accept or decline based on profitability and current circumstances. Profits earned from executing orders can be reinvested to optimize the factory, purchasing additional machines or expanding operations, such as acquiring more AGVs. Players also tackle troubleshooting and maintenance tasks as they arise. Challenges are presented within specific time frames.

3.6 Adaptability

Our concept embodies adaptability and flexibility due to its versatile design and comprehensive approach to education. By integrating both physical and digital learning environments, we provide educators with a range of options to tailor their teaching methods to diverse student needs and preferences. The open character of the tools allows for the incorporation of new tasks related to specific topics, fostering a dynamic and evolving learning experience. Learners can select between using the available resources - physical models, digital twins only, the combination of the two, or the VR mode - based on their learning preferences and objectives.

As previously discussed, the VLP accommodates learners with varying levels of prior knowledge, signified by the learning levels integrated into the environment. These levels denote the extent of complexity or abstraction in reflection and action that participants should aim to attain within a subject area. A particular strength of the concept lies in the flexible organization of time. Learners can choose from different subject areas and levels to adapt the lessons to their individual needs and learning progress. Additionally, the teaching concept allows the teacher the flexibility to adjust the time allocated to the virtual environment and the practical work with physical models.

The division of the course into learning phases with different focal points based on features in the virtual learning environment, such as introduction through exploration and application through the task area, is intended to promote understanding and application of the content. The teacher should regularly incorporate feedback from participants regarding time management and course structure to enable continuous improvement. This requires periodic reflections from the learners on the progress to date.

4 IMPLEMENTATION

The implementation of the learning environment is based on the virtual engineering software PolyVR. This software provides simulation and emulation modules for virtual twins of machines and production facilities, as well as data and dynamic protocol-based interfaces (Häfner, 2019) . It also provides some degree of platform independent deployment, Linux and Windows, and visualisation capabilities on most VR platforms such as CAVEs, Powerwalls and VR headsets.

4.1 Tangible Learning Factory

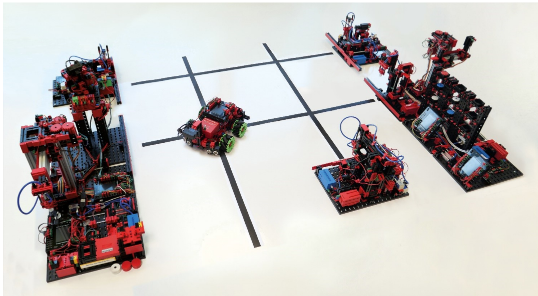

Figure 2: Agile Production Simulation 24V learning factory, a product by fischertechnik company.

With the Agile Production Simulation (APS), fischertechnik has introduced an innovative model of a learning factory that is intended to reflect the flexibility and modularity of modern factories, while offering an easily accessible and user-friendly experience (see figure 2). The Agile Production Simulation system includes various modules like incoming and outgoing goods, high-bay warehouse, milling station, drilling station and a quality assurance with AI on an area of 129 x 184 cm (fischertechnik, 2024).

At incoming and outgoing goods the inbound and outbound logistics occur. Here the workpieces are fed into the real factory and delivered after processing an order. This is where the material flow of a workpiece begins and ends. The raw material is delivered at the goods receipt, positioned on the color sensor for quality control using the 6-axis robot with vacuum gripper, and then encoded on the NFC reader. The robot then places the workpiece on the AGV for further transport. The module also contains the central control unit (Raspberry Pi) and the environmental sensor, which measures the different environmental conditions in the factory. The integrated, movable camera can be swiveled in two axes and provides an insight into the entire factory via the fischertechnik cloud dashboard. At the end of a cycle, a finished workpiece is delivered at the goods dispatch by the AGV.

The next stop for a workpiece after goods receipt is usually the high-bay warehouse. It contains nine slots for workpieces, a stacker crane, and a vacuum gripper that picks up the workpiece from the AGV at the docking station and hands it over to the stacker crane for storage. The workpiece is placed in a workpiece carrier for storage. Retrieval is done according to the First In First Out (FIFO) principle.

The drilling station consists of a docking station for the AGV, a vacuum gripper that places the workpiece onto a conveyor belt, from where it is transported under the drilling head. After the simulated drilling process, the workpiece is transported back to the gripper on the conveyor belt. The gripper then places it back onto the AGV. The milling station is constructed in exactly the same way as the drilling machine, simulating the milling of pockets.

In the quality assurance module, a vacuum gripper places the workpiece on a conveyor belt. It is transported underneath the camera and scanned there. The workpieces, which come in three different colors (white, red, blue), with three machining features (drilling, milling, drilling and milling), as well as various fault patterns, are classified using the trained AI. Depending on the color, feature and fault pattern, the workpieces are then either placed back onto the AGV or sent to the reject container.

A driverless transport system, automated guided vehicle (AGV) transports the workpieces from one module to another. It is a track-bound vehicle that follows the printed black tracks. It uses ultrasonic sensors to detect obstacles. The vehicle has omniwheels, which allow it to move in all directions. Two buttons and a phototransistor help the vehicle dock to individual factory modules. The factory's expandable design allows for the addition of components like kilns, extra machining stations, and supplementary driverless transport systems (fischertechnik, 2024).

The factory is also seamlessly linked to the fischertechnik cloud via a WLAN router, providing access to a web interface which also serves as a dashboard offering several functionalities like real-time monitoring of orders, customizing the task on different colored workpieces, ordering workpieces, factory status visualization, performance metrics analysis etc. Individual factory modules are interconnected physically using a tongue and groove mechanism, forming a cohesive baseplate. New modules can be seamlessly integrated into the existing structure, offering configurability and scalability facilitated through the dashboard interface.

4.2 Virtualization Process

The virtual twin of the Agile Production Simulation accurately mirrors the tangible factory model and its modules. The immersive digital twin incorporates 3D models of each module into a virtual environment, merging them with dynamic-kinematic data, controller programming, and production simulation. This integration yields a fully operational and interactive model of the APS, accurately replicating the authentic behavior of every module. It offers a comprehensive simulation of the execution of all processes within the factory, including those involving kine-

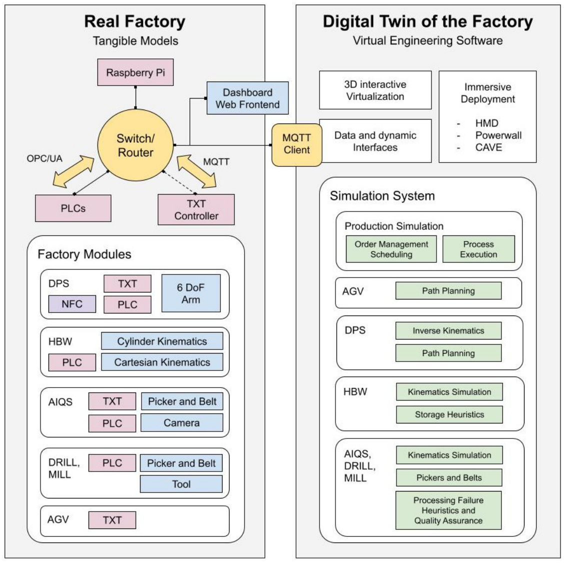

Figure 3: Software Architecture.

matic, mechanical, electrical, and pneumatic systems, with meticulous detail. The digital twin utilizes existing planning data, such as CAD and controller (PLC) programming, to analyze and integrate them, ensuring precise replication of the real factory's behavior within a virtual environment across diverse simulations. For example: a logistics simulation was set up for the Automated Guided Vehicle system. Here paths on which AGV drives are defined and then with the help of a path planner the shortest path to the destination is planned and executed in order to optimise the transport routes for the AGV. Various indicators and factors like transport and processing times, defect rates and throughput are computed and compiled for the user. This allows him to compare alternative processes or optimize a process regarding those indicators.

The digital twin can be used in two modes: Software-in-loop and Hardware-in-loop. In the software-in-loop mode, the virtual simulation is not connected to the physical learning factory (APS). The digital twin operates independently, facilitating teaching and factory operations solely within the virtual environment. Conversely, in the hardware-in-loop mode, the real factory connects to the digital twin through MQTT, enabling synchronization between the virtual and physical systems as well as controlling factory processes from the virtual environment. When synchronizing, the state of the real factory is replicated in real-time in the virtual environment. An ideal level of synchronisation would be on sensor and actuator level, but in the case of the APS these signals are not present on the bus for efficiency reasons. This means that the synchronisation is limited to the

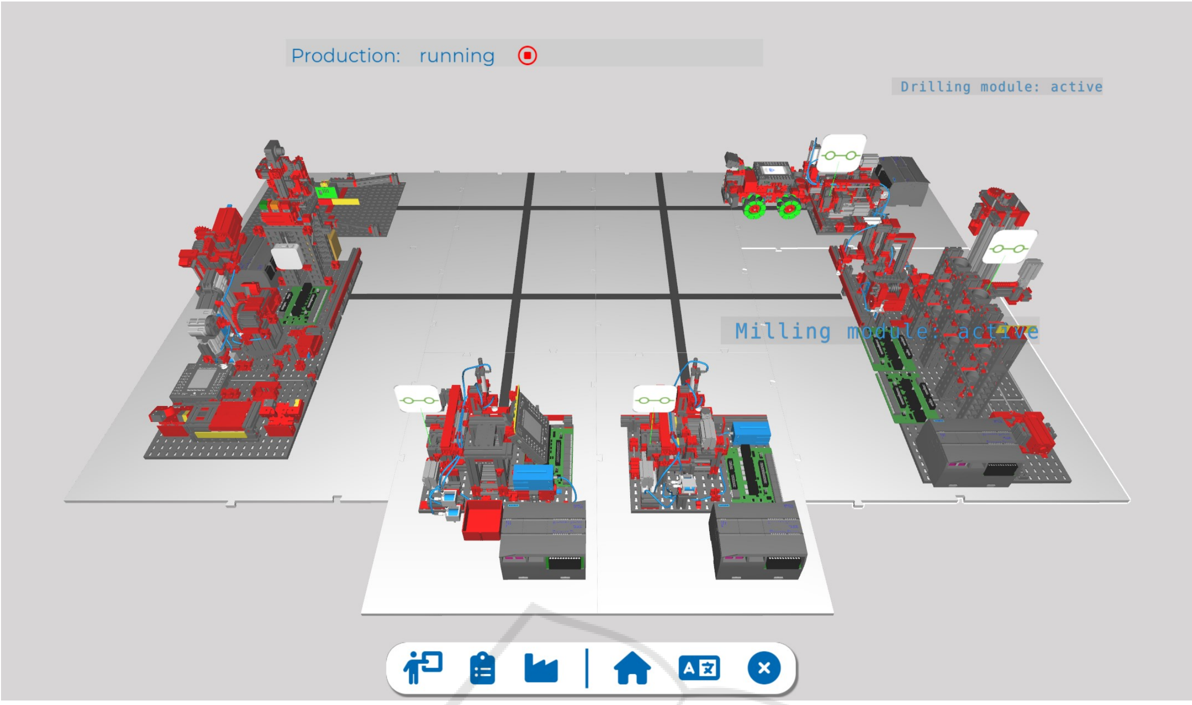

Figure 4: Immersive digital twin of the Agile Production Simulation learning factory.

process control level. This approach provides a more authentic representation of real-world factory operations within the digital twin. Automatic synchronization mechanisms continuously update the status of both the physical and virtual factories, guaranteeing coherence between the two environments in real-time. Bidirectional communication capabilities empower users to not only monitor, but also actively control the real factory through interactions with the virtual model. This integration facilitates a dynamic feedback loop, where adjustments made in the virtual space directly impact the physical production processes.

The creation of the factory simulation can be described in the following steps. The mechanical components have been segmented and simulated using the geometry analysis and mechanical simulation modules of the virtual engineering software. Many optimizations of the scene-graph were necessary to create motion groups and kinematic chains. The 6 Degrees of Freedom (DoF) robotic arm was also simulated using the inverse kinematic solver included in the virtual engineering software. The wiring was not provided as dataset, thus the actuators and sensors had to be manually mapped to IDs in the PLC programming. Those programs have been studied to get a complete understanding of the module behaviors. This was necessary to validate the parsing and execution of the programs in the virtual environment and develop missing components to fully process the programming data. Finally, a process planning, scheduling and execution system was implemented, tailored to the capabilities of the APS.

4.3 Adaptive Virtual Learning Platform

The virtual learning environment comprises a user interface designed to offer distinct modes tailored to different learning needs. The introduction of the VLP to the user is realized with a start screen, describing the three main areas:

- Introduction APS. The user can explore the Agile Production Simulation factory digital twin by examining the production modules, or clicking on individual components for detailed explanations.
- Learning Environment. The user can choose a learning module from the topics provided in the learning environment.
- Simulation Environment. Enables the user to plan, simulate, and analyze production processes using the planner and analysis tools, or simply start a demo simulation process.

Additionally, the start screens offer the option to change the language and provide explanation to input device controls, as well as a video introduction to the main tools.

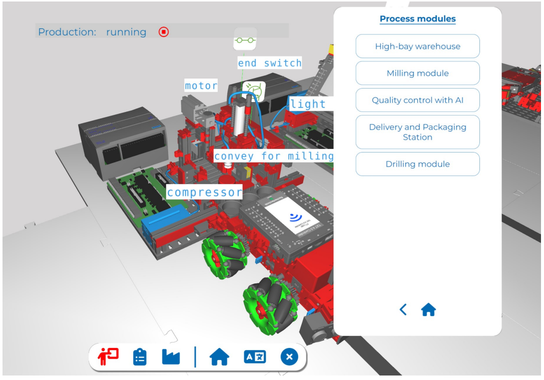

Figure 5: Introduction of the milling module with camera flight and meta data.

In the introduction area, the VLP features animations demonstrating the assembly of baseplates and modules, along with a menu allowing users to select either a process module or a technical component (see figure 5). Selecting a technical component from the list will highlight it while making all other geometries transparent (see figure 6). Users have the freedom to explore the virtual factory without limitations, becoming acquainted with its layout and technical elements. Clicking on 3D objects triggers a widget displaying an image and explanation of their function. This exploratory approach fosters curiosity and self-directed learning, empowering individuals to navigate the factory at their own pace.

In the learning environment mode, users access educational material organized in learning modules and designed to educate them about various aspects of factory operations. Here, learners tackle specific tasks across different categories within the realm of Industry 4.0. The ability to identify various components in the virtual twin performing specific tasks adds a hands-on dimension to the learning process, allowing users to apply their knowledge and problem-solving skills in a realistic environment. Moreover, the option for learners to select one category at a time enhances the convenience and user-friendliness of this mode. The VLP has tasks in different levels of difficulty (as described in section 3). For instance, the first level tasks are called ”find and click tasks”, which should recall the function and the place of a technical component in a factory. An example of such task in the learning module ”Industrial Internet of Things” is as follows: ”A typical communication protocol in the IIoT area is MQTT. This requires a broker. Which component of the fischertechnik APS provides the broker functionality?” Figure 7 illustrates the task list widget associated with the selected learning module, specifically the module ”Agile Production.” This module encompasses various tasks, including those related to agile warehousing, analysis of product throughput, optimization of layout, and parallelization of processes for two workpieces.

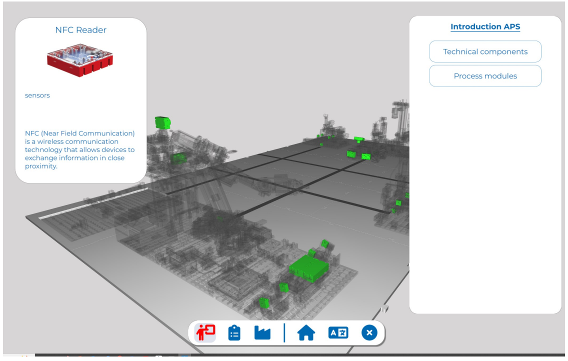

Figure 6: Highlighting the sensors in the virtual factory.

To configure a process, the Agile Production Planner tool was developed (refer to figure 8). Once the process is configured, users can initiate the simulation and observe it within the virtual environment. Subsequently, statistics for the simulated process, such as throughput, can be analyzed using the analysis tool

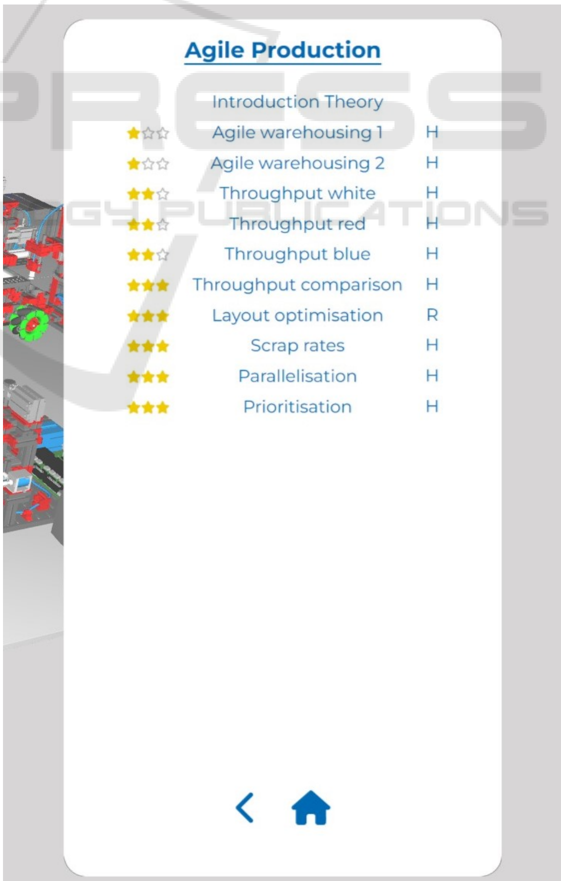

Figure 7: VLP Tasks List for learning module ”Agile Production”.

Figure 8: Agile Production Planner.

(refer to figure 10). The simulated process can also be sent to the real factory and executed there, which enables the teaching of virtual commissioning process.

Meanwhile, simulation environment presents interactive simulations that allow users to apply their knowledge in practical scenarios, thereby enhancing their understanding and skills. Here, educators can propose additional tasks for simulation, or learners can experiment freely.

4.4 Usability

The implementation of the virtual learning platform prioritizes usability for learners, particularly for CAVE and VR headset deployment, where several usability features were considered. These include the use of audio output for text, such as theory descriptions and tasks, to alleviate the challenge of reading extensive text, especially on older VR headsets. Additionally, the user interface employs large buttons designed for easy interaction in the virtual environment using ray casting.

Introduction to the tool is facilitated by video explanations of key tools and tooltips for buttons, while navigation follows a common thread, ensuring users can easily locate needed functionality. Tasks to be solved in the 3D environment, whether on desktop or immersive hardware, are planned to utilize controllers without the need for text input or parameters via keyboard, focusing heavily on interaction with the immersive twin.

The VLP adopts a task start and stop paradigm, allowing users to validate their input or cancel tasks as needed. Upon entering a solution, visual and audio feedback indicates success or failure with the task. Furthermore, extensive metadata visualization

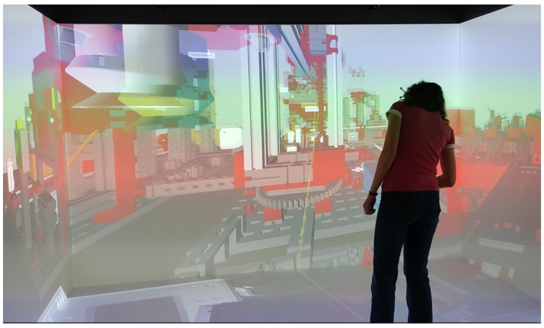

Figure 9: Deployment on CAVE System.

enhances understanding of the factory environment, such as the depiction of active actuators or sensors via pictograms.

In virtual reality mode, scaling factors such as 1:10 replicate real factory dimensions to immerse the user effectively (as depicted on figure 9).

5 EVALUATION CONCEPT

Given that the Virtual Learning Platform and the APS factory have only very recent been introduced and integrated into the educational framework, this section outlines a proposed strategy for designing an effective evaluation and assessment process.

The VLP has been developed to support learners in training within Industry 4.0, with the aim of equipping them with essential specialist knowledge, enhancing existing skills and fostering an understanding of the connections between workflows and business processes. This comprehensive educational approach emphasises both formative/accompanying and summative/final evaluations, facilitating continuous adaptation and optimisation of the teaching approach. By using an integrated evaluation model that combines the strengths of the CIPP (Context, Input, Process, Product)(Stufflebeam, 1971) and Kirkpatrick models (Kirkpatrick, 1959), the effectiveness and efficiency of VLP can be comprehensively assessed. The CIPP model provides a comprehensive framework focusing on context, input, process and product for programme evaluation, while the Kirkpatrick model specifically assesses training effectiveness at four levels: reaction, learning, behaviour and results, with an emphasis on learning outcomes and organisational impact. These models, when integrated, provide a robust evaluation framework that not only measures immediate learning outcomes, but also promotes a deep understanding of effective learning processes. This integrated approach ensures that VLP remains responsive to the evolving needs of learners and Industry 4.0.

Figure 10: Agile Production Analysis Tool.

Data collection to evaluate the VLP is carried out by measuring the outcomes and impact of the teaching approach on learners, including the acquisition of knowledge, skills and competences related to Industry 4.0. The evaluation will be carried out using a variety of tools, such as surveys to identify learners' needs, stakeholder interviews, expert evaluation of teaching materials and methods, teacher and student feedback, observations, performance tests and competency assessments. According to Kirkpatrick, the reaction, learning, behaviour and outcomes of the VLP are recorded to assess learning, using similar tools to those used in the CIPP model. In this way it is possible to compare the results of different teaching approaches.

A comparative study is recommended in order to evaluate the results of the new approach. It is recommended to carry out a study with three groups of learners at each of the three learning levels (see section 3. "Teaching approach"). In this way the results at the different levels can be compared and the suitability of the VLP approach for different VET (vocational education and training) target groups can be analysed. In this design, three groups of test subjects would be randomly assigned for each learning level: a first group whose training would use only the physical learning factory, a second group whose training would use only the VLP virtual learning environment, and a third group whose training would use both the physical and VLP virtual learning environments. For each group, the same instructor would teach exactly the same content with the same learning objectives. For meaningful results without confounding factors, it would be crucial that all three groups contained subjects with the same or at least very similar prior knowledge. In addition, the learning tasks used in the training programmes should have exactly the same indicative, coarse and fine learning objectives, as well as the same Bloom's levels within the taxonomies (cognitive, affective, psychomotor).

To summarise, the VLP offers an innovative approach to Industry 4.0 education, but the implementation of the proposed comparative study poses significant practical challenges. Coordinating three different learning environments to subject groups of three different learning levels illustrates the complexity of effectively evaluating educational technologies. Despite these difficulties, such research is essential for the improvement of the VLP and must be tackled in the future - perhaps not even comprehensively, but at least selectively.

6 CONCLUSION AND FUTURE WORKS

The developed learning environment shows how a combination of practical application, digital technologies and innovative teaching methods can help to optimally prepare future specialists for the requirements of Industry 4.0. The use of fischertechnik agile factory and its digital twin creates a unique learning experience in a hybrid manner, which can be adapted to several heterogeneous user groups and teaching setups. The implemented features in the VLP offer a comprehensive and immersive learning experience, ensuring users can seamlessly explore and comprehend the factory environment. It also provides users with an overview of Industry 4.0 applications within the virtual or physical factory. Through process modelling and analysis tools, users gain insight into the relationships and interactions among various elements and processes in the factory environment, leading to a holistic understanding of procedures. Future work will focus on the development of further learning modules such as robotics and maintenance.

We are planning a long-term evaluation based on the proposed concept, but also strongly limited by the potential users and available funding.

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