Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 130 (2024) 743–748

www.elsevier.com/locate/procedia

57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024)

Fostering Digital Competences: A Modular System and Practical Training for Digital Twins

Christian Kuhn[a,*], Julian Hermann[a], Thorge Lackner[a], Dominik Lucke[a,b]

[a]*Hochschule Reutlingen, ESB Business School, Alteburgstraße 150, 72762 Reutlingen, Germany*
[b]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany*

* Corresponding author. Tel.: +49-7121-271-3158; fax: +49-7121-271-90-3158. *E-mail address:* Christian.Kuhn@Reutlingen-University.de

Abstract

Digital twins enable real-time monitoring, analysis, and optimization, thus enhancing efficiency and productivity in future factories. Nevertheless, the effective integration and innovative future utilization requires the broad acceptance and understanding among non-IT-related groups. This paper presents a practical training program that provides detailed guidance on how to create digital twins from real world data. It consists of modules utilizing 3D models in Unity with associated code, MQTT connectivity and network addressability. The integration of real-world data combined with a user interface that displays values in an integrated space enhances the overall usability. This integrative approach based on low-cost hardware and open source software makes the technology accessible to a wide audience and opens up new opportunities for advances in related higher education and employee training.

© 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024)

Keywords: Digital Twins; Internet of Things; Training Programme

1. Introduction

The integration of Internet of Things (IoT) technologies and digital twins enables a key enhancement of industrial processes in future factories. Through real-time monitoring, analysis and optimization an enhanced process efficiency and productivity can be realized [1,2]. The adaption of these technologies is increasingly essential for maintaining competitiveness in the global market. However, a major challenge is to ensure the acceptance and understanding of these technologies among non-IT-related groups, such as engineering students and workers. They often lack the technical knowledge to utilize IoT and digital twin-based tools, which requires a comprehensive understanding of their advantages and disadvantages. Furthermore, companies lack the resources to train their employees in these advanced skills, further widening the gap in technical expertise [3]. This highlights the need to develop targeted training programs to close this knowledge gap. Particularly in the field of industrial engineering education, it is essential to provide knowledge of IoT and digital twin technologies for higher education as they will inevitably come into contact with those tools in future careers. The first step is to understand the difference between digital twins, digital shadows and digital models. A digital model is based on a manual exchange of data between the physical and digital world. A digital shadow transfers data automatically from the physical to the digital world, but manually back to the physical world. The digital twin has an automatic data transfer in both ways. No manual exchange of data is required [4,5]. Based on this definition of digital twins, the overall concept and the composition of physical and digital components are explained. As a digital twin is very complex, a modular approach was chosen to break down the complexity and highlight specific aspects of an application.

The paper focuses on fostering a deeper understanding of these fundamental concepts and is capable of supporting higher

2212-8271 © 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024)
10.1016/j.procir.2024.10.158

education and staff training tailored to the needs of non-IT-related groups. Thus chapter 2 reviews relevant literature on learning models for digital twin technology and their state-of-the-art. Chapter 3 introduces the training concept developed and outlines all required modules in detail. After the validation using the 'Digital Box' and an industrial CNC machine, Chapter 5 shows the main learnings of the authors and chapter 6 discusses future research activities.

2. Related Work

Digital twins provide a basis for teaching and learning and enhance industrial processes. Teaching methods for digital twins and the use of modular digital twins in industry are therefore analyzed and evaluated.

2.1. Learning Methods for Digital Twin Technology

In the field of digital twin technology, the intersection of education and innovation is both promising and complex. In exploring the education landscape, several key aspects emerge.

The first aspect is, that in developing new training approaches for digital twin technology, the importance of STEM (science, technology, engineering and mathematics) education has to be recognized. STEM provides the foundation for training future digital twin experts. One approach is the OECD Learning Compass 2030 [6]. This describes what teaching could look like in 2030. The organization aims to support education systems in identifying the skills, knowledge, values and attitudes that students need to succeed.

The second aspect is, that existing literature often focuses on teaching applications and use cases of digital twins. However, there is a gap, that few publications address the inner workings of digital twins themselves. And when focusing on this, they often present a general outlook on the possibilities of digital twins rather than a concrete implementation [7].

The third aspect is, that classroom environments are rapidly evolving and shifting to digital technologies. As smart classrooms become more prevalent, educators face the challenge of ensuring that learners understand these technologies. A desirable outcome would be that students not only use digital twins, but also understand the underlying principles behind them [8].

By considering these three aspects, it can be concluded that digital twins are more than just tools. They are a foundation for future teaching and learning. However, the complexity of their development must not be underestimated. This leads to the conclusion that the complexity of digital twins must be adapted. One possible solution would be modularization, but this involves examining what digital twins currently resemble.

2.2. Digital twins today

Today, digital twins offer a multi-layered approach to understanding and interacting with real-world values. Persistence, insight and explainability [9] are at the core of their functionality. Digital twins permanently reflect real-world assets and provide a dynamic representation that evolves with the physical system. This dynamic representation provides users with valuable insights and enables informed decisions based on real-time data and simulations. However, to truly harness the power of digital twins, explainability is key. Users need to understand how digital twins make predictions and recommendations so that they can trust the insights they provide and use them effectively. Validation, analysis, prediction and improvement [9] are key areas in the field of digital twin technology, as well-constructed and integrated digital twins offer a wide range of possibilities. Validation ensures that digital twins accurately replicate physical systems and provide an accurate representation of reality. Analysis uses the data collected from the digital twin to uncover patterns, trends and anomalies to optimize performance and efficiency. Simulation and predictive capabilities enable optimization, proactive maintenance and risk mitigation by forecasting potential problems before they occur. Finally, improvement involves continuous refinement of the digital twin model, incorporating new data and insights to improve accuracy and effectiveness over time. Together, these processes form the foundation of digital twin technology, enabling better understanding, decision making and management of complex systems.

Based on these aspects, digital twins can be used in many areas. In the planning of cities [10], in agriculture [11] or in industry [12]. Especially existing modular digital twins were examined, offering insights and applications. One approach is to break digital twins into modular components, focusing on specific aspects such as data analysis and virtualization. This approach emphasizes the granularity of modular design, where individual modules represent different functionalities rather than the entire digital representation of an asset [13]. In another study researchers examine a different perspective on modular digital twins by using a UR10 robot with integrated sensors. In this approach, the hardware components are already fully functional allowing for a comprehensive and practical representation of the physical system. Therefore, the entire machine was seen as a module, which differs from the level of modularity presented in this paper [9].

In addition, modular digital twins have been applied to specific systems, such as flow management and energy systems. Studies show the effectiveness of modular designs in facilitating system assessments and improving the understanding of complex processes. However, the focus is not on the reuse of modules in cross-domain digital twins but rather on industry-specific use cases. The modules were also defined differently, as they reflect the individual technologies and processes and not the interactions from the physical to the digital object [14,15]. Despite the potential benefits of modular digital twins shown, retrofitting existing systems with digital twin functionality remains a challenge. Current research shows that there is a lack of established retrofit concepts with digital twins, highlighting an area for future research and development [16].

In conclusion, digital twins show remarkable versatility and are very promising for various applications, including learning

and teaching. Nevertheless, the complexity of developing digital twins is often an obstacle to effective training. Modular digital twins offer a solution by simplifying the learning process and enabling untrained workers to understand the complexities of digital twin technology. Due to the flexible selection and arrangement of modules, both simple and highly complex digital twins can be created. As research in this area continues to evolve, the modular digital twin presented is capable of laying a critical role in shaping the future of digital twin training and application.

3. Training Concept

The modular training concept enables non-IT-related groups to build an IoT system based on individual modules and transfer these into a digital model without any further effort. This allows simple production-related systems to be reproduced and simulated.

When developing the training concept, it was taken into account that the participants neither have a technical understanding of IoT and digital twins nor have mastered the basics of programming. The modular approach was chosen so that different technologies can be adapted, allowing use cases to be built up in a structured manner. Especially in the field of higher education and staff training, it is important to keep the costs of a training concept as low as possible so that the application is not limited to financially strong institutions. For this reason, attention was paid to the price of the software and hardware and generally freeware or open source software was used.

The objectives in developing the training concept were to create an understanding of technologies in the field of IoT and digital twins. The focus is on data generation, data processing, data analysis and visualization, as these form the foundation for the digital twin.

As the core component of the training, a simple machine represented by a box was first equipped with a microprocessor, sensors and actuators and then digitally modelled. This enables the interaction of the modules to be demonstrated and the interaction between the physical objects and digital objects to be shown. The box itself has been optimized for training purposes. It is compact and portable, so that training courses can be conducted directly in companies or classrooms without any special infrastructure. The training concept itself is structured in several stages to address participants with different levels of knowledge and objectives. From a holistic hands-on training with data acquisition and processing to the lecture over the construction of modular digital twins to the pure presentation of the results, all training options are covered. However, in order to create a holistic understanding of the concept, the understanding of the module architecture and the interaction between the modules is crucial.

4. Module Structure for the Digital Twin

The modules of the digital twin follow a self-developed architecture, which was subsequently verified through technical implementation and training. Apart from the training box a CNC milling machine was implemented as a digital twin based on this architecture and transferred with other assets into an industrial application.

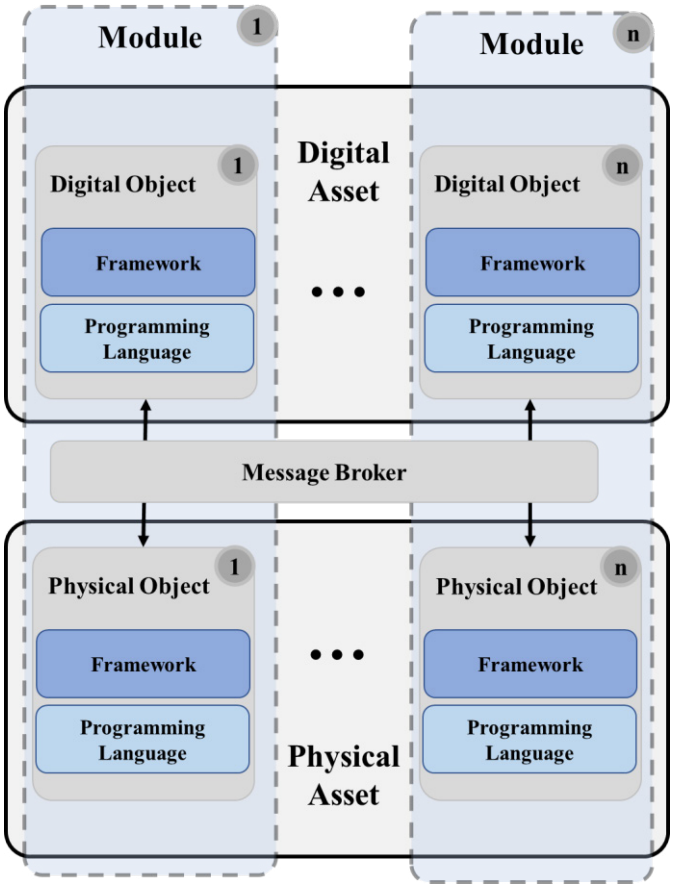

Fig. 1. Architecture of the modular digital twin

4.1. Architecture of the modular Digital Twin

The architecture of the modular digital twin primarily explains the interaction between digital and physical assets and the interaction between individual modules. Physical assets in this context can be microcontrollers, microprocessors or entire machines. Each physical asset is divided into a large number of physical objects, representing a sensor, actuator or other hardware component. A physical asset is thus divided into fine granularity based on the functionality of individual objects. The objects themselves consist of a framework, which can also be integrated across objects, and an underlying programming language. This holistic approach is illustrated in Fig. 1. An example of this is a microcontroller (physical asset), which is equipped with a temperature sensor (physical object), which is controlled and read out with the Arduino framework based on the C/C++ programming language. The resulting data is forwarded to the digital asset with a message broker. The digital asset itself consists of a number of digital objects, whereby each digital object is a representation of a physical object. The actual form of the representation is not specified, making it possible to use a 3D model or simple dashboard to

visualise data. This is again based on a framework and the corresponding programming language. For example, the microcontroller as a 3D object (digital asset) can visualise the data of the temperature sensor (digital object) via Unity (framework) based on the C# programming language.

The modularity and flexibility of this architecture therefore comes from the number of underlying possibilities. If the physical objects in a physical asset can be controlled using the same framework and the same programming language, the overall complexity of the system is reduced. In addition, due to the modular structure, only the relevant data of a physical asset can be read, which significantly reduces the effort required to implement this solution.

4.2. Technical implementation in the training context

Based on this architecture, the 'Digital Box' shown in Fig. 2, a real object that was extended by a digital twin, was created. The box itself consists of a 3D-printed housing and contains a microprocessor with sensors (Raspberry Pi), which represents the physical asset. The individual objects are a rotary encoder with display, a color sensor, a distance sensor, temperature and humidity sensors and an OLED display. The framework used to control the individual objects is Node-Red, a block-based graphical development tool based on HTML and JavaScript. This was expanded to include scripts in Python, which enable the sensors to be read and actuators to be controlled. Each sensor can therefore be regarded as a block. The data is then sent to the digital asset with MQTT as a message broker. The digital asset is a 3D model created in the gaming engine Unity. Each of the modules is based on the C# programming language and enables direct processing of the data received by the message broker. Only the functions that are relevant for understanding were modelled here. For example, the change in position of the rotary encoder is not mapped in the 3D model, but the mode of operation in the physical and digital object can be interpreted with the connected display and the number shown on it.

Fig. 2. Digital Box

For the training concept, this means that learners can control each sensor and actuator connected to the microprocessor individually and independently of other objects. The data can also be retrieved and displayed locally, which means that all physical assets are functional even without the digital image. This teaches how sensors are read out and actuators controlled, which protocols are used for this and how the interaction of the individual objects can function. Depending on the scope and length of the course, this approach can be can be enhanced by delving into the framework or the fundamental programming principles, and directly programming the objects themselves instead of relying on pre-developed blocks for this purpose. Once the hardware and software foundations have been laid when looking at the physical asset, a connection to a central server with a message broker is established. This is where the messages are orchestrated and sent to the digital asset, the digital image in Unity. Here it is as well possible to drag and drop a 3D object into the user interface and then work with it, or to carry out the programming yourself. The training concept can therefore be customized vertically by adding or omitting the network capability and the digital asset and horizontally by adding or omitting physical assets or physical objects.

This training concept is designed not only to be used in a teaching context, but also to demonstrate the possibilities and challenges of a digital twin. A CNC milling machine was therefore created as an additional physical asset and converted into a digital asset based on the architecture presented.

4.3. Technical realization based on a real Machine

Due to its nature, the CNC milling machine has a large number of possible physical objects that can be extracted and controlled. For this reason, only the core functionalities of the machine were mapped during implementation. Live data of the DNC connection, the door status, the machine control panel related to the DNC connection, the machine status as well as the tool status with feed speed, rotation speed and position are monitored. Additionally, the progress of the program is tracked. With these functions, even a highly complex CNC milling machine can be controlled and monitored by non-expert personnel. The possibilities and challenges of creating a digital twin are also demonstrated here. In addition to the

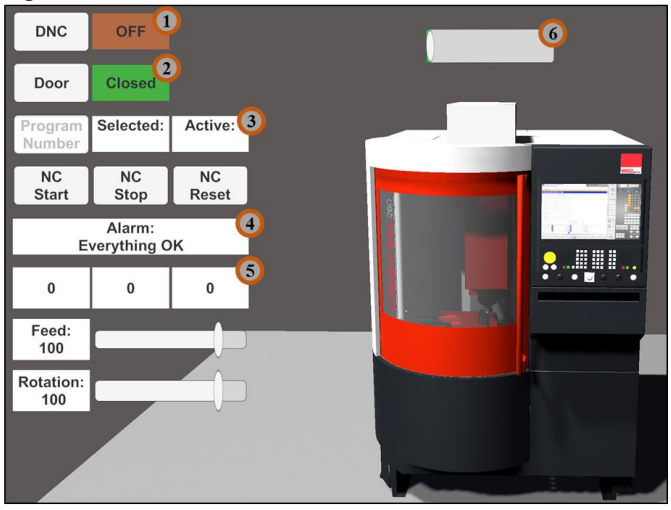

Fig. 3. Visualization of CNC milling machine

hands-on approach, the participants in the training course also learn the complexity of such applications. The 3D visualization of the digital twin is shown in Fig. 3.

Thanks to its modular structure, the CNC milling machine can be expanded to include different number of sensors in both physical and digital space. A temperature sensor with a microcontroller was integrated in the machine room on an experimental basis. The original physical asset (CNC milling machine) was thus expanded to include another asset (microcontroller). Communication takes place via the same message broker. Based on these theoretical principles, the practical implementation of the architecture was validated and tested at several events.

4.4. Development of real-life competences

The training concept approach helps to create real-life competences by explaining the structure of a digital twin based on the 'DigitalBox'. Here, the developed architecture is applied and a connection between physical and digital assets is established. Data is exchanged automatically and the physical asset is influenced by analysing the data in the digital asset. The transfer of simple modules in the training context to a more complex digital twin is realised by integrating a CNC milling machine. It is extended by individual modules, thus creating a modular system of an industrial machine. The aim here is to create the transfer from a teaching environment to an industrial environment. The objective for non-IT-related groups is to gain the ability to understand the complexity of a digital twin and to transfer the acquired knowledge to other objects in an industrial context.

5. Validation, Evaluation and Main Learnings

The training concept was validated on a technical level by integrating several physical assets into an overall system. The focus was on testing different architectures of physical assets. The CNC milling machine was extended with a microcontroller that monitors the temperature via a sensor and a microprocessor that records vibration signals via MEMS vibration sensors during a milling process. By analyzing the vibrations with a machine learning model, workpiece defects such as blowholes can already be determined during the milling process. Due to the interconnectivity of the physical and digital assets, the machine can be stopped immediately in the event of serious quality defects.

Table 1. Scope of the trainings

Scope of the training	Working solution	Module approach	Framework Coding	Coding basics
Holistic hands-on training in the area of IoT and digital twins	**X**	**X**	**X**	**X**
Hands-on introduction to the interaction of IoT and digital twins	**X**	**X**	**X**	
Lecture on the construction of modular digital twins	**X**	**X**		
Presentation on the interaction of IoT and digital twins	**X**			

In the area of training, several training courses were conducted and analyzed. The training courses had different depths of implementation, which meant that everything from holistic hands-on training to pure presentations of the concept were carried out, as shown in Table 1. Over a period of six months, the concept was presented seven times, taught once, conducted twice as a hands-on introduction and once as holistic hands-on training. The feedback was acquired through responses from the participants after the training courses. The results from students and employees in industry were positive for both non-IT-related and IT-related groups. Focusing on the technical feasibility of the overall concept, feedback was obtained and the general acceptance of the training was analysed. This led to the most important learnings for the developers of the training concept:

- The architecture for the modular digital twin enables the simple creation of complex structures and the connection of several physical assets in an overall system.
- Split assets into objects enables fine-grained applications and adapt training for specific use cases as well as frameworks and programming languages.
- When implementing the modules, attention must be paid to the uniform structure and an interface analysis must first be carried out in order to standardize data.
- During training, a real use case should always be used as comparison to create a connection to the industrial context.
- A digital twin must be abstracted so that only system-relevant functions are mapped. Unnecessary details reduce the efficiency of a digital twin and diminish the success of training, as a high level of complexity is created.

6. Conclusion and Further Development

The increasing demand for well-trained workers and students with knowledge in areas such as IoT and digital twins reflects the growing importance of these topics in the industry. Educational institutions and companies are therefore faced with the challenge of raising awareness of these key areas. There is a need for a new way to make digital twins tangible in a training context without losing the practical relevance. In this paper an innovative approach that meets these requirements is presented. The presented training concept is based on a modular architecture creating a link between the physical and digital world and incorporating various hardware and software components. Additionally, the training concept can be implemented at different levels, allowing for broad integration into courses. The only limiting factor is the availability of open source software and hardware and the technical know-how to transfer these into the modular structure.

Further research activities aim at selecting and interviewing training experts who understand the intricacies of building and managing digital twins. Based on the feedback, the architecture

will be improved and more assets will be integrated into an overall system to create a versatile environment for training.

References

[1] Attaran M, Attaran S, Celik BG. The impact of digital twins on the evolution of intelligent manufacturing and Industry 4.0. Advances in computational intelligence; 2023;3(3):11.

[2] Da Silva Mendonça R, Oliveira Lins S de, Bessa IV de, Carvalho Ayres FA de, Medeiros RLP de, Lucena VF de. Digital Twin Applications: A Survey of Recent Advances and Challenges. Processes; 2022;10(4):744.

[3] Falcone R, Sapienza A. On the Users' Acceptance of IoT Systems: A Theoretical Approach. Information; 2018;9(3):53.

[4] Fuller A, Fan Z, Day C, Barlow C. Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access; 2020;8:108952–71.

[5] Kritzinger W, Karner M, Traar G, Henjes J, Sihn W. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine; 2018;51(11):1016–22.

[6] OECD. OECD Future of Education and Skills 2030 Concept Note: Conceptual learning framework. Learning Compass 2030 ttps://www.oecd.org/education/2030-project/teaching-and-learning/learning/learning-compass-2030/OECD_Learning_Compass_2030_concept_note.pdf (accessed 19 March 2024).

[7] Crespi N, Drobot AT, Minerva R. The Digital Twin in Action and Directions for the Future. In: Crespi N, Drobot AT, Minerva R, editors. The Digital Twin. Cham: Springer International Publishing; 2023. p. 1201–1217.

[8] Purdue Online. The Evolution of Technology in the Classroom. https://online.purdue.edu/blog/education/evolution-technology-classroom (accessed 19 March 2024).

[9] Douthwaite JA, Lesage B, Gleirscher M, Calinescu R, Aitken JM, Alexander R, Law J. A Modular Digital Twinning Framework for Safety Assurance of Collaborative Robotics. Frontiers in robotics and AI; 2021;8:758099.

[10] Ketzler B, Naserentin V, Latino F, Zangelidis C, Thuvander L, Logg A. Digital Twins for Cities: A State of the Art Review. built environ; 2020;46(4):547–73.

[11] Pylianidis C, Osinga S, Athanasiadis IN. Introducing digital twins to agriculture. Computers and Electronics in Agriculture; 2021;184:105942.

[12] Dubarry M, Howey D, Wu B. Enabling battery digital twins at the industrial scale. Joule; 2023;7(6):1134–44.

[13] Rolle RP, Martucci VdO, Godoy EP. Modular Framework for Digital Twins: Development and Performance Analysis. J Control Autom Electr Syst; 2021;32(6):1485–97.

[14] Panarotto M, Isaksson O, Vial V. Cost-efficient digital twins for design space exploration: A modular platform approach. Computers in Industry; 2023;145:103813.

[15] Arrano-Vargas F, Konstantinou G. Modular Design and Real-Time Simulators Toward Power System Digital Twins Implementation. IEEE Trans. Ind. Inf; 2023;19(1):52–61.

[16] Laukotka FN, Krause D. Supporting Digital Twins for the Retrofit in Aviation by a Model-Driven Data Handling. Systems; 2023;11(3):142.