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MODULAR DIGITAL TWINS: THE FOUNDATION FOR THE FACTORY OF THE FUTURE

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ABSTRACT

Companies face stiff challenges regarding their value chains' circular and digital transformation. Digital Twins are a valuable and powerful tool to ease such transformation. Yet, Digital Twins are not just one virtualized model but several parts with different functions. This paper analyzes Digital Twins' frameworks and reference models on an architectural level. We derive a modular framework displaying best practices based on empirical data from particular use cases. Hereby, we concentrate on discrete manufacturing processes to leverage benefits for the factory of the future. According to a design science cycle, we also demonstrate and evaluate the modular framework in a real-world application in an assembly line. The study provides an overview of the state-of-the-art for Digital Twin frameworks and shows ways for easy implementation and avenues for further development. As a synthesis of particular architectures, the modular approach offers a novel and thoroughly generizable blueprint for Digital Twins.

1 INTRODUCTION

Digital Twins are a phenomenon that has become an integral part of today's economic reality. Especially within the last five years, the concept has gained a foothold in the industry. They are now used in many domains and are fundamental to business processes (Attaran and Celik 2023; Strobel et al. 2022). A Digital Twin, as a virtual image of a physical element, combines systems, models, data flows, and data processing, i.e., simulation, mathematical optimizations, or AI-based analyses (van der Valk et al. 2022). Digital Twins' applications help save billions of dollars if rigorously implemented (Thomas 2024).

Many market surveys, trend studies, and technology radars show that the Digital Twin has grown from a technology in its infancy to a market-ready product (cf. BMW 2024; DHL Trend Research 2024; Gartner 2018; Kolarsch et al. 2023). With such a mature product, initial approaches to standardization are to be expected. Naturally, these also exist. They include the ISO standard 23247 (ISO 23247 2021) or the standardization undertakings of the Industrial Digital Twin Association, i.e., the Asset Administration Shell (IDTA 2023), as well as other institutions such as the Digital Twin Hub Britain or the Digital Twin Consortium USA. Numerous attempts have been made in the academic literature to develop a structuring framework, such as a reference model. At the same time, the subject area of the Digital Twin thrives on the fact that comprehensive practical implementations already exist.

However, this market is highly segregated, and it is difficult to inductively identify matching features and architectural elements of a Digital Twin (Fortune 2024). In addition, a closer look at the individually existing frameworks and reference models reveals another unique feature of the topic of Digital Twins. There are two streams in the development of the Digital Twin concept. One originates from the simulation community (van der Valk et al. 2020). Here, the Digital Twin is primarily seen as an evolutionary extension of simulation technology (cf. Boschert and Rosen 2016). The other stream looks at product lifecycle management, where the Digital Twin primarily appears as an integrated data transfer, storage, and processing entity (Grieves 2023).

As a result, the different frameworks and reference models are just as diverse as the entire subject area of the Digital Twin - at the same time, it must always be ensured that the structuring approaches describe a Digital Twin of modern understanding. This particularly applies to the differentiation from digital shadow, virtual models, or digital threads. Nevertheless, a valuable lesson can be learned from analyzing the different frameworks, structuring works, and standardizations. This is because, at an elementary level, there is a great deal of overlap between the individual structures. A synthesis is capable of displaying best practices between the different frameworks. Additionally, context-dependent frameworks can be generalized.

Thus, the research objective (RO) is to show which modules a Digital Twin consists of based on existing reference models, standardization norms, and other structuring frameworks.

To answer the RO, the paper is structured as follows. First, the theoretical background about Digital Twins in general, as well as about modular systems in industrial ecosystems, is provided. We outline the combination of research methods in the following section. We start with a detailed presentation of the analyzed frameworks for the results part. The explanation of the extracted modules follows suit. The emerging modular construction is demonstrated, evaluated, and discussed in Section 5. Lastly, we provide our contributions, limitations, and paths for further research.

2 THEORETICAL BACKGROUND

Digital twins are initially defined as the interaction of a physical space with a virtual space and the associated data connections (Grieves 2014). Although the concept became known primarily in the context of product life cycle management, it has always had a close connection to simulation technology (Glaessgen and Stargel 2012; Grieves 2023). However, the concept of the Digital Twin is a very integrative environment for simulation applications, data processing algorithms, data collection and sharing initiatives, and the representation of real systems (van der Valk et al. 2022). Over time, the concept evolved from this 3-tiered approach into a much more granular concept. In the meantime, a Digital Twin also includes the environment and the provision of services (Tao et al. 2019). Other works that consider the Digital Twin at a very elementary level are, for example, the taxonomies by Enders and Hoßbach (2019) and van der Valk et al. (2020), or the characterization by Jones et al. (2020).

In addition to the components of the macro level, which are the physical object and virtual model, the data flows between the two, the services offered, and the peripheral environment. Other elements are added at the micro level, such as bi-directionality, internal data processing, storage, and synchronization between the physical and digital environment, or possibilities for automating the same (Jones et al. 2020; Kritzinger et al. 2018; van der Valk et al. 2022). In the meantime, the research focus has shifted from elementary investigations to an application-oriented research paradigm. Nevertheless, it remains a very heterogeneous field of research in which regular analyses of the ontological structure are profitable.

3 RESEARCH METHOD

The underlying research method for this endeavor is the well-proven design science research (DSR) approach (Peffers et al. 2007). Their approach incorporates six steps (cf. Figure 1): problem identification, RO definition, design of the artifact in question, demonstration, evaluation, and communication of the results. For the problem identification, motivation, and the concrete objective, one is redirected to Section 1. The DSR cycle addresses the RO and will produce an overview of the Digital Twin's modules.

The research interest in Digital Twins has evolved over the last years. Thus, the first attempts have been made to develop structuring frameworks for Digital Twins, such as reference models or architectures. Therefore, the design phase will unfold in two steps. First, a structured literature review (SLR) is conducted to determine the modules of Digital Twins used in generic reference models, frameworks, and architectures.

This SLR follows the approach of vom Brocke et al. (2009). Hence, we define the review scope as papers that report on reference models, architectures, or frameworks that describe the Digital Twin on a modular level within industrial contexts. To gather the publications, we searched for the term "“Digital Twin” AND “reference model” OR “reference architecture” AND production OR logistics OR supply’ in the database Scopus. We focus on descriptions in the domains of production and logistics, i.e., the industrial contexts. As logistics and supply chain (management) are often used synonymously, both terms are added to the search string. Yet, *supply* seems to be a sufficiently abbreviated form for many terms starting with supply. We explicitly search for reference models and architectures. Although these terms describe two different aspects, they are often used synonymously (Garcés et al. 2020; Reidt 2019).

The search yielded 89 hits searching within the titles, abstracts, and keywords. Nevertheless, a more detailed analysis reduced the number of relevant hits to nine frameworks. The other publications either did not comply with quality standards, such as rigorisity and a transparent framework development, were irrelevant to our research, or were inaccessible. Each relevant framework is then analyzed for its modular description of a Digital Twin in the second design step. Each module is noted. The different modules are named similarly in streamlining to gain comparability, creating an overview matrix. Based on this matrix, a component diagram emerges describing the various modules. We implemented the so-developed structure within a demonstrator case called MINIS to demonstrate the artifact. During this demonstration, we also evaluated the modular structure according to well-established verification and validation techniques. The implementation uses the implementation process model for simulation models (Verein Deutscher Ingenieure 2014). Lastly, the modular structure is communicated through this paper.

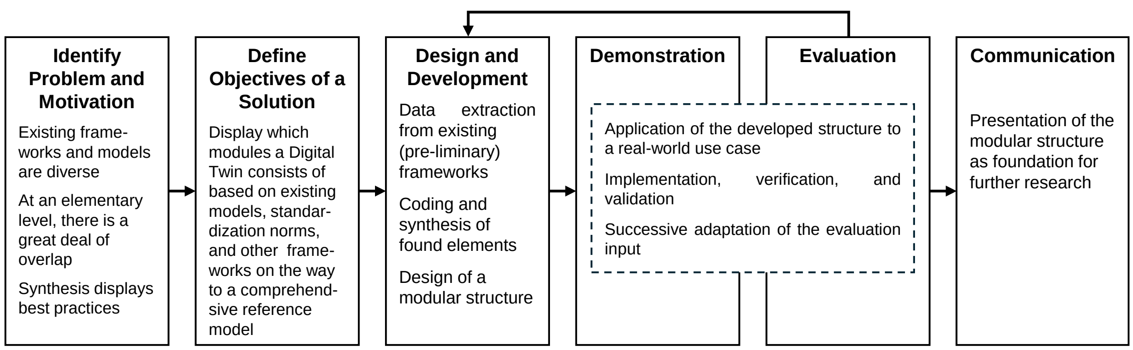

Figure 1: Research Method – The DSR cycle.

4 MODULAR DIGITAL TWINS

4.1 Review of the relevant Reference Frameworks

In order to determine the modules of a Digital Twin, the literature search and desk research results are evaluated below. Although we rely on existing frameworks for our research, we derive a new concept. The analyzed frameworks do not all describe a full Digital Twin. Furthermore, they are partly focused on very tight applications. Thus, our aim for a more diverse and truly fitting framework remains unanswered.

(1) The oldest model of the analysis is that of Lu and Xu (2018). This model takes up Grieves’ original definition and has the physical object, the digital object, a data model, and the communication paths between the physical and digital object as core elements.

(2) Another model is by Aheleroff et al. (2020). Their model contains five elements: a physical layer, a digital layer, an application space, a cyberspace, and a communication layer. This model is based on RAMI 4.0 and, therefore, also adopts the layer structure of the original. However, its approach excludes bi-directionality, which is required as an explicit component of a Digital Twin (van der Valk et al. 2022).

(3) The third hit is the model by Bibow et al. (2020). This describes an already very detailed architecture. The model has four layers. Here, too, there is an application and a connection layer. There is also a data layer and a cyber-physical layer. The latter represents the physical twin and is designed as a

black box. There are interfaces for data communication from this layer, but no further details exist. The data layer consists of databases grouped together in a data layer. Various data streams, e.g., raw data, queries, or commands, also flow between the layers. The connection layer contains the data processing. In detail, these are data processors and so-called executors. Both are connected to the various elements of the application layer. This layer contains the information about the physical system. Based on this, the calculations are carried out based on the objectives of the Digital Twin (Bibow et al. 2020).

(4) The fourth approach comes from Latsou et al. (2021). It is based on the five levels of cyber-physical systems. The overall model is, therefore, also based on the physical element. The lowest level is the physical level, above which is the data level of the physical object. For example, this can be state data, which can be immense. The third level, which is in the middle, is responsible for the data transfer between the physical and digital sides and is called the cyber layer. The fourth level is the database, and finally, the fifth level contains the functionalities of the Digital Twin. The model of the physical versus stop is also found here. However, the entire framework focuses on cyber-physical systems and, therefore, does not include all the mandatory characteristics of a Digital Twin. In addition, they concentrated solely on data transfer via RFID. Bi-directionalities or other data communication options are not considered (Latsou et al. 2021).

(5) The fifth framework by Marinković et al. (2023) is a very detailed architecture. It is based on the ISO 23247 (2021) standard, which proposes a reference architecture for Digital Twins. However, this proposed reference architecture of the ISO standard does not yet include a Digital Twin but a digital shadow according to the generally valid characterization (cf. Kritzinger et al. 2018).

Marinković et al. (2023) extend the ISO standard and present an ecosystem architecture consisting of various objects. These are categorized into four main entities: user entity, device communication entity, observer manufacturing element, and Digital Twin entity. The architecture of the Digital Twin here consists of a database and a so-called solution space. Although the model is one of the most advanced, it is aimed more at the general ecosystem in which the Digital Twin is located than at the twins themselves, which is why the specifications are relatively high-level except for a database and a solution space (Marinković et al. 2023).

(6) The following framework is also based on the RAMI framework (Mendonca et al. 2025). It contains five layers. The physical layer is on the lowest level. This layer includes the physical system, e.g., conveyors, robots, or sensors. The next layer is the data layer. All data flows between the physical and virtual sides can be found in this layer. Here, the data is also processed for quality and data management aspects. The integration layer is the third one. It aims to connect systems and operations via the Internet of Things (IoT) technologies. The fourth layer is the service layer. All data operations are located here, e.g., condition monitoring or fault identification. Lastly, the upper layer is the decision layer, which includes the objectives and management goals the Digital Twin shall meet (Mendonca et al. 2025).

(7) The model of Antunes et al. (2024) consists of a total of seven modules, whereby the majority of these modules are arranged in a hierarchical layer configuration. The lowest module of the physical infrastructure includes cameras and physical goods such as vehicles or products. The data from this physical module goes to the so-called data module. Here, among other things, the data from IoT applications is integrated. Via HTTPS protocols, this data from the data layer goes into the IT infrastructure layer. The infrastructure layer supports the so-called application layer. Among other things are real-time representations, data storage in blockchains, and operations management functions. Through corresponding portals, e.g., GUIs or apps, the user, who forms an additional layer, i.e., the actors layer, communicates with the Digital Twin. In the form of a media break, the user layer lies between the application layer and the service layer. The services themselves are then, for example, operations control, vehicle control, or a terminal operations function. All hierarchical layers are accompanied by the so-called content level, representing the 7th module (Antunes et al. 2024).

(8) Ryu et al. (2024) propose an architecture for Digital Twins that is closely aligned with the Asset Administration Shell, a communication protocol for industrial data sharing. Their architecture contains four elements. First is the nameplate submodel, which includes all metadata. The technical data submodel incorporates all technical data necessary for the operation of the physical object. The OPC UA Server

Access Submodel is used for communication. This submodel is responsible for the data transfer via OPC UA. Lastly, the operational data submodel contains all state information of the physical object (Ryu et al. 2024).

(9) The last framework to be considered is that of Lim et al. (2024). They present a complex system comprising Digital Twins and other entities surrounding them. These include, for example, the user, cross-system, observable processes, and Digital Twin entities. The link itself consists of several modules. The digital marketplace offers various services of the Digital Twin, which communicate directly with a blockchain platform. The marketplace is primarily available to exchange master data from customers and suppliers. The two services of real-time monitoring and decision support are closely linked to the service marketplace. The first tracks and monitors logistics objects in real time. The second carries out various scaling and waiting time analyses. Both communicate with dashboards and 3D visualization. These form the Visualization module. There is also the data storage module, where various relational and non-relational databases can be found. All logistical information, such as the delivery schedule, can also be found here. The Digital Twin itself is then surrounded by multiple communication modules (Lim et al. 2024).

In total, 32 elements emerge from the relevant works that will be processed further in the following section.

4.2 Derivation of Digital Twins' Modules

The 32 elements, as mentioned earlier, contain duplicates among themselves, as they stem from different sources. Thus, the individual elements will be synthesized into modules that do not contain duplicates. For instance, Mendonca et al. (2025) speak of a physical layer, while a corresponding entity is called a physical element by Marinković et al. (2023). In the following, these entities are called physical modules. Analogously, the other 31 elements are synthesized. Table 1 provides an overview of the elements addressed by the nine existing frameworks.

Table 1: Overview of modules per framework.

Modules	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
User Module	–	–	X	–	X	–	X	–	–
Physical Module	X	X	X	X	X	X	X	–	X
Environment Module	–	–	–	–	–	–	X	–	X
Communication Module	X	X	–	X	X	X	X	X	X
Data Storage Module	–	X	X	X	X	X	X	X	X
Service Module	X	X	X	X	X	X	X	–	X
Visualization Module	X	–	–	X	–	–	–	–	X

The remaining seven modules are the Communication Module, Data Storage Module, Service Module, Visualization Module, Environment Module, Physical Module, and User Module (see Figure 2). The first four modules display the Digital Twin. The latter three modules reflect the periphery. Between the modules, there are bi-directional data flows. The definitions of the modules follow the knowledge retrieved and synthesized from the frameworks explained beforehand.

User Module: the first module is the user. Depending on the use case, this person can be an operator of a machine or a conductor in logistics cases. The user interacts with the Digital Twin via the communication module. As with every communication within this system, the interaction between the user and the communication module is bi-directional (cf. Section 2).

Physical Module: the physical module represents the system portrayed by the Digital Twin. This can be a machine, a product, an asset, or a moving vehicle. On the peripheral side, the physical module is the most important one. The communication between the physical module and the communication module is manifold. As Kritzinger et al. (2018) and van der Valk et al. (2024) establish, bi-directionality is mandatory. Yet, the physical module may contain a multitude of different data acquisition tools, e.g., sensors for the positioning of goods or their velocity. Simultaneously, there are paths for communication to pass on system-management requests.

Environment Module: this module includes all further peripheral elements. These could be external databases for historical data, additional applications, data processing options, and system siblings. The peripheral systems communicate bi-directionally with the communication module.

Communication Module: all interactions with the Digital Twin run through the communication module. Thereby, this module may use established communication protocols, such as MQTT, OPC UA, or other interoperable formats. As the distinction between different types of Digital Twins shows, a Digital Twin may be interoperable with the periphery per sé or via a translator (van der Valk et al. 2022). These translators are located within the communication module. Furthermore, a Digital Twin may be situated within a data space. A data space is a decentralized organization with the goal of data sharing in a trustworthy environment (Guggenberger et al. 2025). Data space connectors are used to communicate within data spaces. Thus, this module may also obtain such a connector, e.g., the Eclipse Data Space Connector. Another option would be the Asset Administration Shell, which allows communication between different entities in an industrial ecosystem. In fact, the Eclipse Data Space Connector and the Asset Administration Shell are integral parts of many industrial Digital Twins.

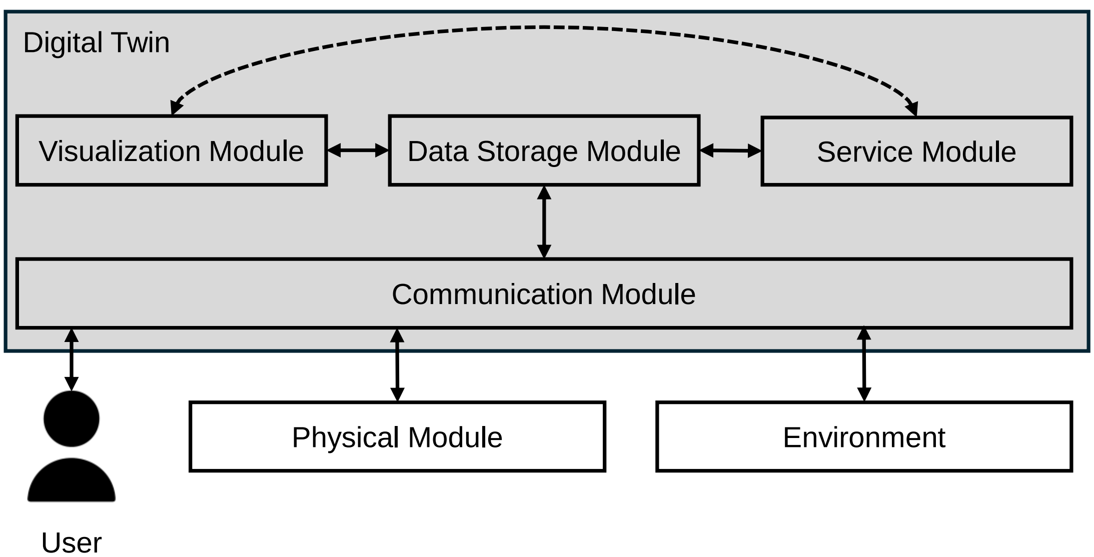

Figure 2: Modules of a Digital Twin.

Data Storage Module: all input and output data runs through the central point of a Digital Twin, the data storage module. This module contains the twins' central database. It can be partitioned into a transient and a persistent database. The data storage, nevertheless, should include all historical data that is needed regularly, as well as all (temporary) calculation data. Furthermore, the data storage module is mainly responsible for the real-time aspect of the Digital Twin. Possible solutions include a Lambda Architecture or, in combination with the communication module, the application of a message broker (Haße et al. 2019; Stuckmann-Blumenstein et al. 2022). The data storage module further distributes the data to the service and visualization modules. Also, it integrates all data backflows and directs the data back to the periphery via the communication module.

Service Module: the service module includes all data processing activities, i.e., simulation, as one of the most essential data services within a twin. This module enhances the ability to predict, optimize, and support decision-making in the physical system. In the sense of a plug connector, activities could be included in the Digital Twin. As previous research showed, simulation applications are most often part of a Digital Twin. Nevertheless, further options include AI-based system optimization, stochastic forecasting, or plain analysis tools. All data used for calculation and the respective results are sent to the data storage module. Yet, a data flow between the service module and the visualization is also possible. Thus, the model part can directly interact with any calculated data.

Visualization Module: the last part of the Digital Twin is visualizing the physical system. In theory, this part's objective is only to display and animate the system, the dynamical and static processes, and changes in the state of any kind. However, the visualization is often part of a simulation service located in the service module. Hence, there is a close connection between both. Nevertheless, a distinction between the simulation and animation parts would be possible. The visualization can also display any data and calculation results coming from the service module and the data storage.

Nevertheless, not all modules are mandatory. In theory, the Digital Twin is operational without the peripheral elements, i.e., the user, the environment, and the physical module. Especially the last one seems odd. Yet, a Digital Twin can be developed before any physical counterpart exists. A second case, where a Digital Twin remains without all elements, would be one with complete autonomy as the goal. Here, no user is needed. Thus, the communication, data storage, services, and visualization modules are deemed mandatory for operationality, while the rest are optional.

5 DEMONSTRATION, DISCUSSION, AND EVALUATION

The modular approach of a Digital Twin is to be tested in a real-world application. For this, the project MINIS is chosen (cf. Stuckmann-Blumenstein et al. 2022). MINIS (Miniatured Production Systems) is a university project and contains a physical demonstration factory. The demonstrator poses for testing and developing innovative technologies around the IoT, Blockchain applications, Digital Twins, smart simulation models, or additive manufacturing. MINIS cooperates with experts from mechanical engineering, logistics, and information sciences. The interaction between the control devices of the MINIS system, its Digital Twin, actors, and sensors aims to enhance the efficiency and flow rates of the production system. Within this context, the modules of the Digital Twin are to be implemented, starting with the physical module (cf. Figure 3).

The physical part is the demonstrator factory as a whole. It consists of LEGO Serious Play parts and further elements that were printed with 3D printers. It contains multiple conveyor belts, sorting stations, and working stations. Goods run through the factory and are manipulated. Further logistics processes can be emulated. The factory is equipped with sensors and actors. The sensors are distance meters. More precisely, HC-SR04 ultrasound sensors are used. Multiple ESP32 microcontrollers coordinate the sensors. The sensors record the exact positions of the goods within the factory. The actors are LEGO Mindstorm EV3 motors. The ESP controllers also regulate the motors.

Entities of the physical module, e.g., ESP32 microcontrollers, already communicate via the MQTT protocol. Due to the existing MQTT infrastructure, the Digital Twin uses the same data interface. Information is shared via JSON messages and tagged with topics and a Quality of Service (QoS). The sending client sets both the topic and QoS. The QoS determines how reliably a message is delivered, and any recipient can subscribe to the topic to receive the message.

Using topics allows the sending client not to know the recipient. Conversely, recipients can use topics to determine which messages they receive. This reduces the implementation effort for multiple and changing recipients, as we find with the Digital Twin. Entities, e.g., models within AnyLogic, only need to have an MQTT interface. AnyLogic is Java-based and allows the use of external libraries. Hence, we use the Eclipse Paho Java MQTT client library for the MINIS implementation.

Within the MINIS implementation, the Data Storage module includes an MQTT broker that runs on a server within the local MINIS network. We use the Eclipse Mosquitto MQTT Broker within a Docker container. The broker stores messages persistently and transiently based on the QoS to ensure recipients receive messages even though the recipient is not online when the message is sent. Besides the broker as the central instance, some MINIS entities also use their own persistent data storage systems. One example is the AnyLogic model, which persistently stores specific parameters and updates them as required. AnyLogic's integrated relational database is used for this purpose.

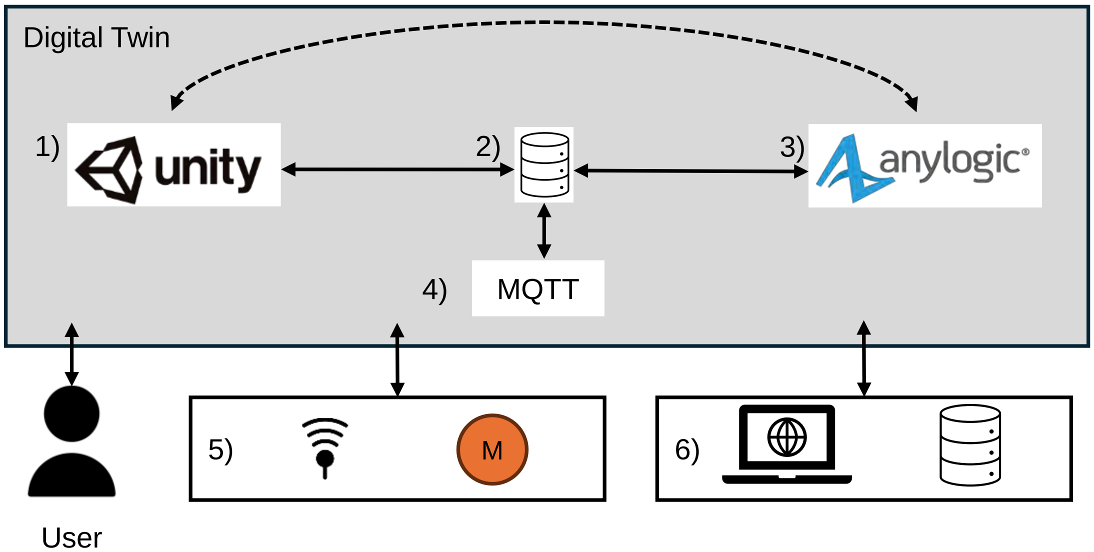

Figure 3: MINIS-adaption to the modules of a Digital Twin.

The demonstrator's animated model stems from the Unity environment. Unity is a well-established software tool for the development of models and is especially favored for designing virtual replicas within the Digital Twin (Garg et al. 2021). Consequently, Capgemini bought the modeling division for Digital Twins from Unity to boost their twin business (Capgemini 2024). The modeler can create the objects of the physical part as 3D models. In this case, CAD drawings of the used elements were available. Thus, they were incorporated into the overall model. All physical components are modeled as unique parts and are then combined into one bigger model. Adherent to the discussion about the granularity of Digital Twins, an image of the physical parts that was as accurate as possible was the aim. Only a few abstractions were made within the animation. The visualization is also synchronized with the movements of the real-world pieces running through the demonstrator factory. Thus, the visualization is already capable of displaying state change, i.e., changes to the locations of the physical parts.

The services offered by our demonstrator focus primarily on discrete-event simulation. Among other things, a series of optimizations of the goods running through the demonstrator factory were examined, and various layouts, work processes, and bottleneck analyses were carried out. In principle, however, the demonstrator is capable of integrating further services. Thanks to the structure, which is similar to a connector strip, other analysis or optimization tools such as SPSS or R-Studio can be docked in addition to the model from Unity and the simulation environment from AnyLogic. The use of AnyLogic as a central service module was also evaluated against using the Tecnomatix Plant Simulation software. In principle, this can also be integrated into the overall model, like AnyLogic, offering comprehensive optimization options. The selection of AnyLogic was purely license-based.

The evaluation addresses two different aspects. On the one hand, of course, the implemented demonstrator is verified and validated. However, at the same time, the modular construct must also be checked for the latter. The first step is to check whether the physical factory's individual systems, components, and processes are correctly mapped in the virtual part of the demonstrator. The structured walkthrough procedure is used for this (Rabe et al. 2008). The individual components are compared with each other in a structured manner between the physical and virtual space, and deviations are recorded and evaluated. The digital part's evaluation also focuses on a functioning exchange of messages between the Digital Twin and the demonstrator factory. Utilizing a test run with secured parameters, the communication between the physical demonstrator via the MQTT protocols and the Digital Twin is tested. By the functioning transmission of the communication paths and the correct representation of the individual elements of the physical demonstrator's static and dynamic nature, it can first be stated that the test implementation is valid and verified.

The evaluation of the modular structure itself is carried out using the six principles of orderly modeling (Schütte and Rotthowe 1998). These are design adequacy, language adequacy, economic efficiency, clarity, comparability, and demonstration of a coherent system structure. These six principles are evaluated argumentatively. The structured approach, the evaluation of the literature, and the derivation of empirical data give the design adequacy. Although no higher modeling language is used, this is not necessary in this case. A block diagram is presented in Figure 2, showing language adequacy. Utilizing an overview image to represent the individual modules simplifies the implementation of a Digital Twin (cf. van der Valk et al. 2024), whereby a higher economic efficiency is given. Which results in greater financial efficiency. The modules are clearly understandable and can also be read by non-experts, and at the same time. They enable the comparability of different implementations and the instantiation of a Digital Twin. Finally, the consistent use of a block diagram with arrows for the data streams ensures a coherent system structure.

Further proof of the usability of the modular model shows the demonstrator's implementability in our MINIS test case. The individual units of the demonstrator factory can be well represented by the various modules of the Digital Twin, thus enabling simplified implementation. The structured approach based on the individual modules allowed the modeling and implementation of the software tools by people who are not native computer scientists. Mechanical and industrial engineers could implement the demonstrator factory in the corresponding software environments. The live operation was possible with plausible parameters. It is, therefore, feasible to transfer the modular structure from our demonstrator case to the business world.

The above-described implementation aligns seamlessly with the Digital Twin Implementation Canvas and the connected process model (cf. van der Valk et al. 2024). The modules find themselves in separate parts of the canvas. As such, the modules show possible implementation process paths, i.e., they can provide an order for developing the Digital Twin. The individual modules can be created using different software tools that are then matched into one Digital Twin. Thus, the combination of the modules creates the twin. This modular way provides easy integration and allows for incremental, agile software development techniques like Scrum.

Nevertheless, despite its flexibility and reusability, a modular approach for Digital Twins is associated with several difficulties and challenges, particularly regarding scalability, data security, and interoperability. In particular, as the number of modules increases, the complexity of managing them also increases, which makes scalability into Digital Twins of any size more difficult. A large number of them must be managed, e.g., in a production system for each machine and each conveyor belt or similar, and this must be multiplied by the power of seven by the maximum number of modules. Each module must also be able to communicate with the other modules, which significantly increases the communication effort itself and also ensures a more complex, interoperable system. Of course, all modules must understand the same language and be able to communicate with each other either directly interoperably or at least via translator interfaces. In addition, many modern interfaces also increase the twins' maintenance and upkeep costs.

Each communication channel also offers a further gateway for hackers, thus jeopardizing the Digital Twin's security. The interfaces must, of course, all be secured against unauthorized access simultaneously. However, modularity also offers the possibility of encapsulating critical areas or areas that have already been infiltrated, allowing the rest of the Digital Twin to continue running with core functions. Suppose the various challenges are planned and addressed at an early stage with a high level of standardization and data governance. In that case, the modular structure of the Digital Twin can simplify implementation and facilitate operation.

The proposed framework allows for easy integration of new modules. In the style of a plug-and-play connection, new elements, such as additional machines, robots, or others, can be integrated into the Digital Twin. The respective module is enhanced, and the new communication avenues are implemented. New elements can easily be modelled in the respective software tools, e.g., Unity or AnyLogic. Theoretically, new modules can also be incorporated into the framework if necessary. Thus, the modular approach allows for a very generalizable development of Digital Twins.

6 CONCLUSION

In this research, we analyzed existing frameworks of Digital Twin to determine the crucial modules a Digital Twin must consist of. Therefore, we searched the literature and identified nine relevant frameworks. Each element of these frameworks was noted and synthesized into one resulting model. The synthesized modular framework contains seven modules: user module, environment module, physical module, communication module, services module, visualization module, and data storage module. The last four create the Digital Twin. To prove the concept, we implemented such a modular approach within the MINIS project in a demonstration factory. The implementation showed that the modular approach eases the implementation and allows non-experts to develop Digital Twins.

Unfortunately, our research underlies certain limitations. First, the classical boundaries of design science and structured literature reviews apply. The work is primarily qualitative. We aimed for as objective research as possible and ensured this through constant reminding ourselves. Nevertheless, we are missing a quantitative point of view and a comparison to other, similar approaches that we will examine in future research. We tested and evaluated our modular approach in a single case study. Multiple further implementations will help to improve all results iteratively. This is also the first path for further research. Nevertheless, the modular approach also allows for the development of design principles for Digital Twins. Furthermore, one can construct an in-depth reference model of Digital Twins, e.g., in UML, to design the modular elements on the elemental level.

Our work provides an up-to-date overview of the state of research for reference models and frameworks for Digital Twins. Scholars can build upon our structured search and analysis. Each of the modules shows promising aspects of further research. Furthermore, researchers can compare their adoption of Digital Twins to this modular approach. Similarly, practitioners can do so. The modules allow for more straightforward implementation, and companies looking to develop Digital Twins may evaluate the risk of building certain modules themselves or outsourcing these modules to specialists. Summarizing the scientific and managerial contributions, the modular approach allows practitioners and researchers to define their individual Digital Twin implementation more thoroughly. The innovation and contribution are the framework and the synthesis of several approaches into one validated, modular structure.

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