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Concept Paper

Digital Twins in Manufacturing: A RAMI 4.0 Compliant Concept

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Abstract: Digital twins are among the technologies that are considered to have high potential. At the same time, there is no uniform understanding of what this technology means. Definitions are used across disciplinary boundaries, resulting in a multitude of different interpretations. The concepts behind the terms should be clearly named to transfer knowledge and bundle developments in digitalization. In particular, the Reference Architectural Model for Industry (RAMI) 4.0, as the guiding concept of digitalization, should be in harmony with the terms to be able to establish a contradiction-free relationship. This paper therefore summarizes the most important definitions and descriptions from the scientific community. By evaluating the relevant literature, a concept is derived. The concept presented in this work concretizes the requirements and understanding of digital twins in the frame of RAMI 4.0 with a focus on manufacturing. It thus contributes to the understanding of the technology. In this way, the concept is intended to contribute to the implementation of digital twins in this context.

Keywords: digital twin; digital manufacturing; Industry 4.0

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1. Introduction

Digital tools are becoming increasingly important in industrial production to improve decision-making processes and deal with increasing complexity [1]. The individualization of products and the resulting decrease in the number of units are a major complexity driver [2,3]. Currently, the high energy prices, at least in Western Europe, and thus the need to consider these in decisions are to be mentioned as an additional complexity factor. In the factory itself, heterogeneous production landscapes and many different systems are mentioned as a challenge in the management of complexity [4]. Digital twins (DTs), on the other hand, offer the opportunity to combine data from different sources to deal with high complexity and thus to support the decision-making process [4,5]. Although DT have been identified in many places as a technology with enormous potential, there is no uniform understanding of the term. This is partly due to the different application areas with their individual questions and requirements. Although DTs were originally developed as a safeguard for in-service objects in [6], most definitions refer to product development or are dedicated to a specific use, e.g., aviation [7]. However, the focus on the product has remained. Approaches to using existing models from development in further life cycle phases have existed for some time. Depending on the timeline in the life cycle of an object, the motivation and thus also the requirement for the DT changes. The classification is usually not considered in the definition, which means that definitions of DT are sometimes contradictory. Therefore, placing the definitions in their context is crucial. Furthermore, the definitions should be compatible with the concepts of digitalization.

This paper brings together the different definitions and provides an overview, and a concept of how DT can support factory operations. In the process of developing the concept, the different developments in connection with DT are addressed. For example, the Reference Architectural Model Industry 4.0 (RAMI 4.0) architecture is worth mentioning in German-speaking countries. This provides a framework for digitizing the factory, so a definition for the DT should be compatible with the RAMI 4.0 architecture. In this way, this work contributes to distinguishing the developments in the area of the digital twin from other digitization efforts, using a clear understanding and thus creating clarity. On the other hand, a superordinate concept is to be created that enables the development of digital twins and architectures based on RAMI 4.0 without contradictions.

2. State of the Art and Research

2.1. RAMI 4.0 Architecture

RAMI 4.0 is a cubic layer model and is defined in the DIN SPEC 91345 [8] (see Figure 1). The dimensions of the cube describe the architecture of assets, their life cycle, and their assignment to a hierarchy level.

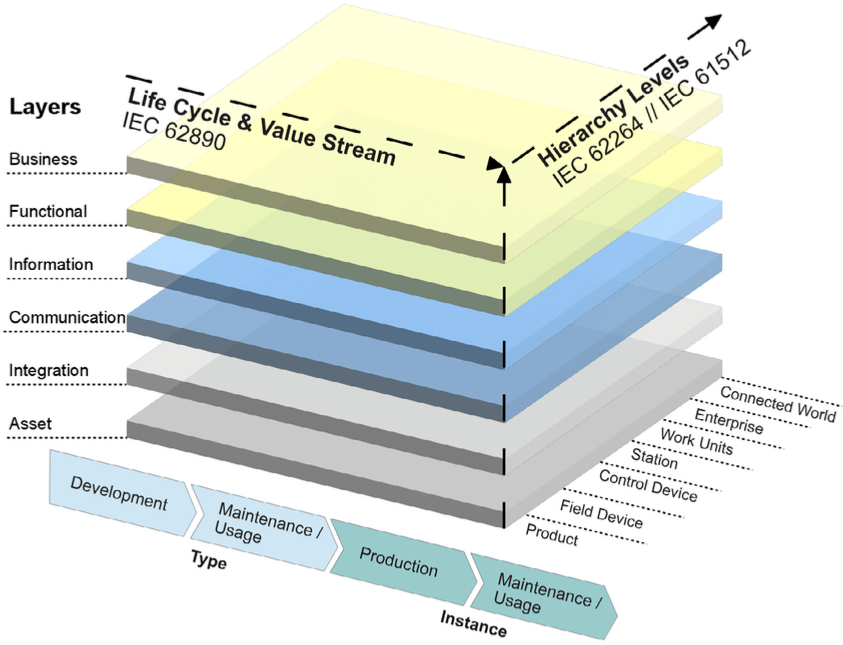


Figure 1. Figure of the Reference Architecture Model Industry 4.0 (RAMI 4.0) (source: [8]).

Layers describe the assets in their respective tasks or functions. The description categories are the classification in the business process, the function of the asset, the information, the communication, and the integration of the physical asset into the virtual world. Not all layers must be used at all times. For integration, the guideline provides the concept of the asset administration shell. In the AAS, the asset can be described digitally, with a communication interface to the physical system. In this way, the AAS can be understood not only as a digital representation but also as a gateway between the virtual and real world. The AAS manages all the essential data for an asset from creation to end of life [8,9].

The life cycle of assets is divided into two sections. The type section describes, as the name implies, the type of asset, i.e., in our example, a model series of a machine as shown in Figure 2. This section of the life cycle consists of a development phase and a utilization phase. In the development phase, when asset properties are defined, the AAS is created in parallel, which manages the general information for this type. As soon as an instance of this type is produced, an AAS is also derived for this instance, which contains information of that type and is additionally specific to this instance. Dynamic data are then added during the operation of the asset.

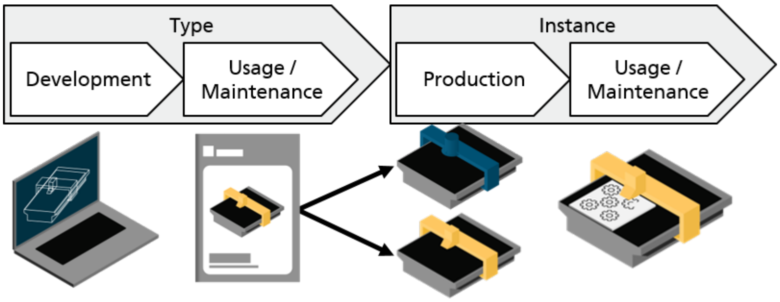


Figure 2. Life cycle of assets (source: own illustration adapted from ref. [8]).

The hierarchy levels place the asset in the factory structure. The axis starts with the product, so the output of an asset is integrated into the consideration as a component. On the other side, the highest level describes the connection to other assets or summarizing instances. In between are the organizational units of the manufacturing process.

2.2. Asset Administration Shell (AAS)

The AAS is part of RAMI 4.0 and defines the description of an asset in the digital space. The two main areas of an AAS are the header and body. The header contains the information required to identify the asset and the AAS. The unique identification is ensured by a uniform resource identifier (URI). The body contains the submodels that describe the functions and properties of the asset. The submodels can be added to the AAS according to the requirements [9]. In addition to the structure, it is advisable to use standardized data models as much as possible and to integrate these into the AAS and to only create submodels in fields in which no standards yet exist. In particular, data models that describe the operation are currently still rare. There is some work that uses RAMI or AAS as the basis for the implementation of digital twins. This includes work that concretizes the reference architecture and derives an architecture for digital twins. These include the work of Beregi et al. [10] and Steindl et al. [11]. Beregi et al. [10] take up the idea of AAS and define a production administration shell (PAS), which should allow plants to communicate with a manufacturing execution system. The idea is to build a modular and interoperable architecture in which resources can be integrated with little effort. Based on the architecture axes, Steindl et al. [11] develop a concrete implementation of an architecture for building a digital twin. Both works deal with specific aspects of RAMI to realize concrete implementations without focusing on the complexity of an entire factory or considering it over its entire life cycle. One work that takes a holistic view of the RAMI architecture is the work of Roscher [12], which applies the RAMI architecture to the energy information system application and develops its own reference architecture in the process. The developed reference architecture is called RAMEnIS6.0, where the life cycle axis is replaced by the energy production axis.

2.3. Digital Twin

Further publications and standards show a different understanding and descriptions of the term digital twin [13–16]. Furthermore, other papers show different stages of implementation or software by which a realization is possible. Concrete requirements for the realization in the context of RAMI 4.0 are not given extensively. This paper attempts to close this gap. On the one hand, Kritzinger et al. [17] show the division of definitions or descriptions of a DT into different categories. Thereby, his study focuses especially on integration levels and the areas within a production (e.g., product life cycle and production planning), and various tools and technologies are addressed (e.g., OPC UA and cloud computing), which are required for the use of DT.

Kritzinger et al. [17] also show in their study that most publications use the description of a **digital model** (DM) or a **digital shadow** (DS), rather than providing a clear definition of a DT (Table 1). This is based on their given understanding of the differences between the digital model, digital shadow, and digital twin, which is elaborated. This differentiation is referred to as the degree of integration. The differences are defined as follows by Kritzinger et al. [17] and is in the broadest sense also addressed by Stark and Damerau [7] and Grieves [18]:

> *A **DM** is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object. The digital representation might include a more or less comprehensive description of the physical object. These models might include, but are not limited to simulation models of planned factories, mathematical models, or any other models of a physical object, which do not use any form of automatic data integration. Digital data of existing physical systems might still be in use for the development of such models, but all data exchange is done in a manual way. A change in state of the physical object has no direct effect on the digital object and vice versa.*

Table 1. Different levels of integration found by Kritzinger et al. [17] in research on the topic of digital twin (source: [17]).

	Concept	Case-Study	Review	Definition
undefined	1.90%	4.76%	2.38%	0.00%
DM	14.29%	11.90%	0.00%	0.00%
DS	26.19%	7.14%	2.38%	0.00%
DT	2.38%	2.38%	9.52%	4.76%

Bearing this in mind, Kritzinger et al. [17] and Bauernhansl et al. [19] describe furthermore as follows:

> ***DS** based on the definition of a Digital Model, if there further exists an automated one-way data flow between the state of an existing physical object and a digital object, one might refer to such a combination as Digital Shadow. A change in state of the physical object leads to a change of state in the digital object, but not vice versa.*

Furthermore, Tao and Zhang [20] as well as Stark et al. [21] define the digital shadow as an essential part of a DT as follows:

> ***DS** is a data profile that couples with the corresponding entity throughout its life cycle, and carries all the data and knowledge to reflect the individual shape and historical, current, and expected future status.*

Based on this clarification, the concept of the three-dimensional DT is established. This concept describes the physical entity, the virtual models, and the data exchange between them as one dimension [18,20,22]. In extension, ref. [23] published the concept of a five-dimensional digital twin (see Figure 3), where services and data are also included in the DT. Colored in red are the parts of the three-dimensional concept, which contains the physical entity (PE), virtual entity (VE), and the connection between them (CN_{PV}). By adding software services (Ss) as well as considering digital twin data (DD) as further dimensions and describing the connections ($CN_{m,n}$) between these four parts as a further dimension, the five-dimensional concept of the DT is created. In addition, Zimmermann et al. [24] explain the term **digital master** as the functional combination of digital twin data (DD) and the virtual entity (VE). At this stage, it is clearly shown that there are many different understandings of the meaning, what a DT is, and which requirements it should fulfill. A literature review is therefore the basis for further discussions and to derive requirements for our approach.

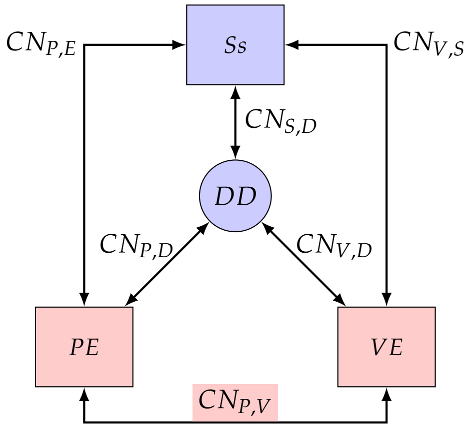


Figure 3. Concept of the five-dimension Digital Twin (source: own illustration adapted from ref. [7,16,23]).

2.4. Research Methodology

To show the need for clear requirements on a definition of a DT, which addresses the complexity of a production system, we conduct a literature review. This review contains a multi-step approach to find and classify relevant requirements and definitions. This approach is based on the procedure used in Glock and Hochrein [25], Hersi et al. [26] and Tawfik et al. [27]. The literature review includes the four superordinate steps:

1. Preparation
2. Planning
3. Screening
4. Classification

which are described in the following.

2.4.1. Step 1—Preparation

The need for a literature review is based on multiple facts. At first the large amount of descriptions of what a DT should be. This takes into account not only understanding but also naming. The terms Cyber Physical Twins [28] or Cyber Digital Twins also exist, which describe the same technological approach. Therefore, we want to collect the key requirements, that a DT must be fulfilled in the context of digital manufacturing. Second, we want to show the combination of the RAMI 4.0 model with the use of a DT, therefore we need a categorization, which is shown in step 4. This is needed to derivate necessary key requirements of a DT in the frame of RAMI 4.0.

2.4.2. Step 2—Planning

For our research, we choose as relevant databases ScienceDirect, IEEE Xplore, SpringerLink, and Web of Science to start a query. As boundaries of the querying only publications since 2000 were considered. For our classification, on the one hand, we cluster the relevant definitions into the topics, related to the RAMI 4.0 model, to product-related or process-related and into the topics general definitions or industry sector definitions. Therefore, our literature review focuses, but is not absolutely limited, on definitions from engineering fields, that means manufacturing, aerospace, electrical engineering, and Industry 4.0.

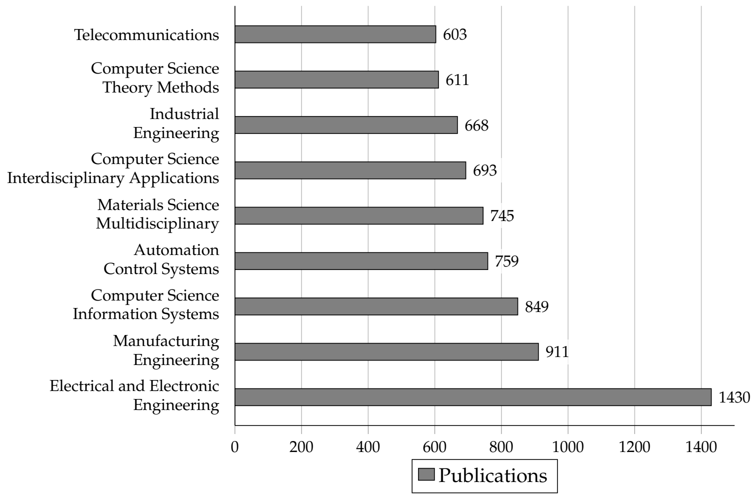
The screening itself contains multiple steps:

1. Check for the right research field of an article.
2. Review the title.
3. Verify the abstract.
4. Check the full text to find descriptions or definitions of the term “digital twin”.
5. Check the references for additional sources.

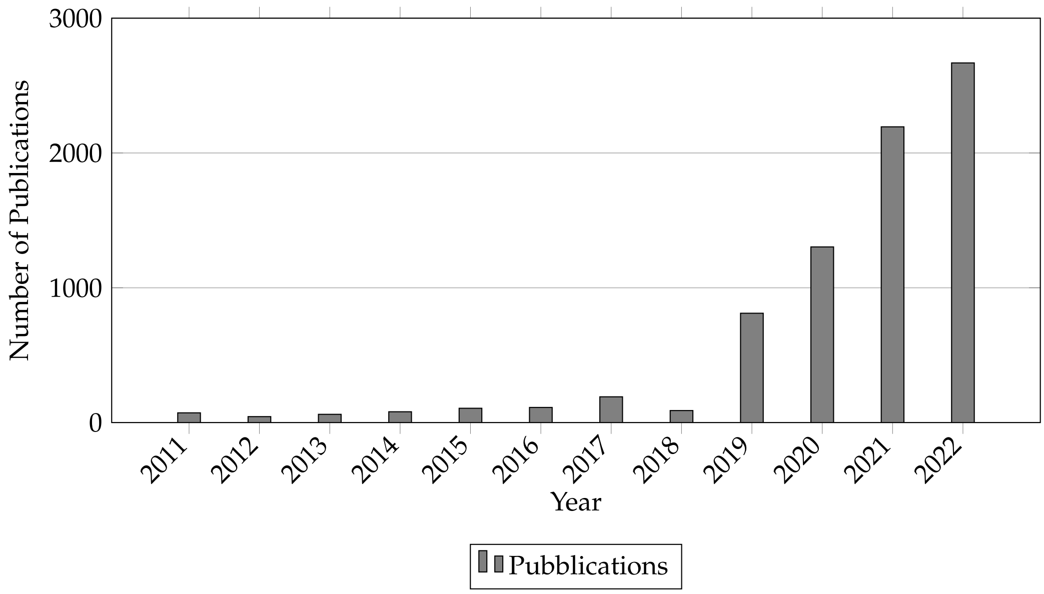
An article was excluded from our study if the article did not fulfill one of these steps.

2.4.3. Step 3—Screening

The results of screening the databases are shown in Figure 4. At first, the relevance of the topic of "digital twin", exemplarily shown in Figure 4b for the query at Web of Science, is proved. It is clearly shown that, in the last six years, research on the topic of "digital twin" has risen significantly. Additionally, Figure 4a shows the distribution of the top 12 engineering fields, where publications with the topic of DT were made. It was found that most publications came from electrical and electronic engineering, followed by manufacturing and computer science. If one of these studies satisfied all steps, this study was considered for our classification.



(**a**)



(**b**)

Figure 4. Statistical screening results of the literature review with (**a**) results from research fields and (**b**) the total number of publications per year (source: own illustration). (**a**) The amount of publications in different research fields is shown in this plot. Thereby, most of the publications were in the field of electrical and electronic followed by manufacturing engineering. (Web of Science 3 February 2023); (**b**) The figure shows the number of publications on the Web of Science database from 2010 to 2022, with the query term "digital twin". Clearly identifiable is the extreme rise of publications within the topic of "digital twin" since 2019. [Web of Science 3 February 2023].

2.4.4. Step 4—Classification

Within our classification, we sort the found descriptions oriented at the different lifecycle steps of the RAMI 4.0 model, production, or process-related descriptions of a DT. Here, seven product-related definitions and four process-related definitions were found. Additionally, 14 descriptions of the term DT in general were made, and 9 descriptions or definitions from industry were found. In the next step, we mark the content of each classified definition as a key element, in the sense that its high-level requirements or functionality is summarized.

2.5. Definitions of Digital Twin

Nearly all found definitions or descriptions of the term "digital twin" explain communication between a real physical asset or entity and a virtual representation, e.g., [14,15,22,29]. Some of them, e.g., [7,17,30], describe more in detail, that this representation is a model based on data which come from the physical asset. In addition, Garetti et al. [31], Kraft [32] and Schleich et al. [33] argue that these models can also handle information from software services. These services can handle different tasks, like prognoses, optimize or control the physical asset [6,22]. For this collaboration between the physical asset, model, and services, data are essentially those of [20,34],which can be measured from the physical asset or the services [32] and from other external sources [35]. This data communication between the data sources, physical asset, services, and models should be in real time [36,37] and use the standardization of all components [29]. An overview of the classified descriptions and definitions is given in Table 2.

Table 2. Table with the classified definitions of the term digital twin and the elements included in each. Marked definitions (*) are not retrievable as full text (not open source) by the authors and come from secondary sources (source: own illustration).

Topic	Reference	Definition	Year	Key Element
Product related definitions	Reifsnider and Majumdar [38] *	*Ultra-high fidelity physical models of the materials and structures that control the life of a vehicle.*	2013	virtual model
	Rios et al. [39]	*Product digital counterpart of a physical product.*	2015	virtual model, real asset
	Schroeder et al. [40]	*Virtual representation of a real product in the context of cyber-physical systems.*	2016	virtual model, real asset
	Manas Bajaj et al. [41] *	*A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system life cycle, federating models in multiple vendor tools and configuration-controlled repositories.*	2016	services, hierarchical, virtual models
	Abramovici et al. [30]	*A virtual twin is a model that integrates interdisciplinary (mechanics, electronics, software, and services) virtual product models and related real-time data of a product instance (physical twin). A virtual twin can be dynamically generated from a model and data space to fulfill a specific task (e.g., dynamic reconfiguration of a smart product during its use phase).*	2017	real asset, virtual models, data, services, hierarchical, real time
	Schleich et al. [33]	*In synthesis, the vision of the digital twin describes the vision of a bi-directional relation between a physical artifact and the set of its virtual models. In this context, the virtual "twinning", i.e., the establishment of such relations between physical parts and their virtual models, enables the efficient execution of product design, manufacturing, servicing, and various other activities throughout the product life cycle.*	2017	real asset, connection, virtual models, services

Table 2. *Cont.*

Topic	Reference	Definition	Year	Key Element
	Grieves [18]	*A digital twin is a distributed and decentralized approach to manage product information at product item level along its life cycle.*	2015	real asset, virtual model, connection, modularization
Process-related definition	Lee et al. [35]	*Coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms and other available physical knowledge.*	2013	hierarchical, real-time, real asset, virtual model
	Rosen et al. [42]	*Very realistic models of the process current state and its behavior in interaction with the environment in the real world.*	2015	connection, real asset, virtual models,
	Bauernhansl et al. [19]	*The digital shadow first transfers the real production process into the virtual world. Based on this, the Digital Twin can deliver an image of reality that is as identical as possible through a process model and simulation.*	2016	real asset, virtual model, services
	Garetti et al. [31]	*The DT consists of a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behavior of the production system at each lifecycle phase in real time.*	2012	virtual model, real asset, services, real time, connection, data, hierarchical, scalability
General definitions	Schluse and Rossmann [43]	*Virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the Internet of Things and services.*	2016	virtual model, real asset, connection, services
	Canedo [44] *	*Digital representation of a real-world object with focus on the object itself.*	2016	virtual model, real asset
	Gabor et al. [45]	*The simulation of the physical object itself to predict future states of the system.*	2016	data, services, real asset, virtual model
	Gartner [34]	*A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organization, person or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant or a city, and their related processes.*	2022	real asset, virtual model, modularization, hierarchical, services, data, scalability
	Kraft [32]	*An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by digital thread, which uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin.*	2016	services, data, robustness, virtual model, hierarchical, real asset
	Söderberg et al. [46]	*Real-time optimization using digital copies of physical systems.*	2017	real-time, real asset, virtual model
	Bolton et al. [47]	*The dynamic virtual representation of a physical object or system throughout its life cycle, using real-time data to achieve understanding, learning, and reasoning.*	2018	virtual model, real asset, real time, data

Table 2. *Cont.*

Topic	Reference	Definition	Year	Key Element
	Tao et al. [23]	*Digital twin uses physical data, virtual data and interactive data between them to map all components in the product life cycle.*	2019	real asset, virtual model, data, connection
	Stark and Damerau [7]	*A digital twin is a digital representation of an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases.*	2019	real asset, virtual model, services, data, hierarchical, modularization
	Rasheed et al. [22]	*A digital twin is defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making.*	2020	virtual model, real asset, services, real-time, hierarchical, data, connection
	Industrial Digital Association e. V. [48]	*Digital representation, sufficient to meet the requirements of a set of use cases.*	2022	virtual model, hierarchical,
	Claude Baudoin et al. [49]	*Digital model of one or more real-world entities, digital twin entities can be objects or processes, that is synchronized with those entities at a specified frequency and fidelity.*	2022	virtual model, modularization, connection, robustness, real asset
	Digital Twin Consortium [37]	*A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.*	2022	real asset, virtual model, connection, robustness
	Kritzinger et al. [17]	*If the data flows between an existing physical object and a digital object are further fully integrated in both directions, one might refer to it as a digital twin. In such a combination, the digital object might also act as controlling instance of the physical object. There might also be other objects, physical or digital, which induce changes of state in the digital object. A change in state of the physical object directly leads to a change in state of the digital object and vice versa.*	2018	data, real asset, virtual model, connection, hierarchical, modularization, real time, services
Industry-Sector definitions	Shafto et al. [50]	*An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems.*	2010	hierarchical, services, virtual model, modularization, scalability,
	Tuegel [51] *	*A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including submodels of the electronics, the flight controls, the propulsion system, and other subsystems.*	2012	modularization, hierarchical, virtual model
	Gockel et al. [52]	*Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements.*	2012	virtual model, hierarchical, scalability
	Bielefeldt et al. [53]	*Ultra-realistic multi-physical computational models associated with each unique aircraft and combined with known flight histories.*	2016	virtual model, real asset, data
	Bazilevs et al. [54]	*High-fidelity structural model that incorporates fatigue damage and presents a fairly complete digital counterpart of the actual structural system of interest.*	2015	real time, virtual model, robustness

Table 2. *Cont.*

Topic	Reference	Definition	Year	Key Element
	El Saddik [36]	*Digital twin is digital copies of biological or non-biological physical entities. By bridging the physical and virtual worlds, data are seamlessly transferred, allowing virtual entities to exist simultaneously with physical entities.*	2018	virtual model, real asset, connection real time
	Negri et al. [29]	*Digital twins are digital representations based on semantic data models that allow running simulations in different disciplines, that support not only a prognostic assessment at the design stage (static perspective) but also a continuous update of the virtual representation of the object by a real-time synchronization with sensed data. This allows the representation to reflect the current status of the system and to perform real-time optimizations, decision making and predictive maintenance according to the sensed conditions.*	2017	virtual model, standardization, data, services, hierarchical, real time, services, connection, real asset
	ISO 23704-1:2022 [15]	*Digital replica of physical assets (physical twin), processes and systems that can be used for various purposes or a fit-for-purpose digital representation of something outside its own context with data connections that enable convergence between the physical and virtual states at an appropriate rate of synchronization.*	2022	virtual model, real asset, connection, data, standardization
	ISO 23247-1:2021 [14]	*Fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation.*	2021	virtual model, real asset, connection, standardization

3. Research Gap

Consideration of the multitude of definitions has shown that there is no uniform understanding and requirements for the term "digital twin". The understanding varies across different areas, but even within the areas, there is often a divergence. Just in the area of manufacturing, a multitude of definitions can be found. Furthermore, there are already more concrete concepts, such as RAMI 4.0. However, RAMI 4.0 provides a reference architecture and with the AAS, a data format. The AAS is therefore not yet a digital twin, as is sometimes simplified. According to the five-dimensional model, for example, the simulation ability is not given in the AAS. The AAS can be more seen as a DS according to the definition by Tao and Zhang [20] and Stark et al. [21] to describe a certain asset. A concept therefore needs to derive how a factory with multiple assets can be modeled. Overall, there is a lack of a concept that links RAMI 4.0, AAS, and the understanding of a digital twin. To establish this connection, the first step is to define what a digital twin is before it can be placed in the context of the RAMI 4.0 standard. The goal should be to find an understanding that is as universally valid as possible and that is consistent with the existing and evaluated digitization concepts. The focus of the objective of the digital twin should not itself restrict the application of the definition. In concrete terms, this means that whatever the target value of optimization within manufacturing, the definition should be adaptable accordingly. In the consideration of the found definitions, some commonalities have become apparent, which are to be highlighted as a basis. Accordingly, based on the definitions given in Table 2, elements of a digital twin in the production area should be the following elements given in Table 3. In addition, a DT consisting of the above elements should have the following capabilities:

- Possibility to automatically control the real asset, also with results from the services.
- Possibility for real-time automatic data acquisition and control.

Furthermore, these eight general conditions, summarized by [20] and also described partly by other authors, should be fulfilled to achieve long-term and sustainable benefits through the use of a DT:

1. Data and knowledge-based (compare Table 3): the most up-to-date data and rules available should always be used in the modeling and in the use phase.
2. Modularization [6,7,17,18,20,34,49,51]: a DT should provide reusability, flexibility and interoperability for a system-of-systems approach.
3. Light weight [17,22,29–31,35,36,46,47,54]: models with maximally low complexity and thus with low computing time to enable the real-time capability of the DT.
4. Hierarchy [6,7,17,22,29–32,34,35,41,51,52]: a DT should use different hierarchical layers for the efficient use of different tasks.
5. Standardization [14,15,29]: to guarantee that all components of a DT communicate efficiently and securely with each other.
6. Servitization [6,7,17,19,22,29–34,41,43,45]: use of standard services for easy and convenient usage of the DT.
7. Openness and scalability [6,31,34,52]: open to interoperate with various resources and scalable, which enables functional extension.
8. Robustness [32,37,49,54]: a DT should be built with good robustness to deal with unpredictable changes.

Based on this list of requirements, an understanding of which elements and capabilities are needed is found. The elements and capabilities are to be concretized in a RAMI-compliant concept to be able to guarantee its implementability in industry. Furthermore, the existing definitions are to be taken into account, and thus a consistency is to be achieved.

Table 3. Elements of a DT which are derived from the different definitions in Table 2 (source: own illustration).

DT Element	Based on Reference
real physical asset/entity	[7,14,15,17–20,22,29–37,39,40,42–47,49,53]
virtual model/entity that describes the real asset (physical, math, 3D models, etc.) and is capable of predicting the behavior of the real asset	all references given in Table 2
data which describe the real physical asset (contains data harvested from the real asset and from services)	[7,15,17,22,23,29–32,34,45,47,53]
services (e.g., monitoring, simulations, prognosis, optimization, and control)	[6,7,17,19,22,29–34,41,43,45]
full connection between the elements (physical asset, virtual model, data and services) for data exchange	[14,15,17,18,20,22,29,31,33,36,37,42,43,49]

4. Conceptual Approach

The conceptual approach is based on the AAS and the result of the overview of the DT definitions. The AAS is used to include the factory assets and to realize bidirectional communication between assets and the factory control level, where the DT is located. The simulation ability on the factory level is realized by a factory model and corresponding services to fulfill these tasks. The factory model uses the information which is supplied by the AAS. The concept displayed in Figure 5 is based on the product-oriented approach to describe the life cycle of digital twins [7] and the RAMI reference architecture [8]. Unlike the DT of a product, a factory is a complex structure of many interrelated individual resources. Each resource, in turn, has its own life cycle. In this case, resources refer to assets that contribute directly or indirectly to the manufacture of the product and are thus modeled in a DT. These can be, for example, production facilities, such as a machine tool from the illustration, or a technical building equipment facility. Each resource has a representation that already includes information from the previous life cycles of this resource, which has been expanded accordingly for individual use in the factory. Furthermore, products and thus digital representations are created or extended anew in the factory. The products to be manufactured in the factory are also represented digitally. In this way, information can be documented in the creation phase, for example, process parameters related to the specific instance. The distinction between products and resources is made only because they are at different life cycle stages. Products are currently being produced, whereas the machines for them are in their usage phase. However, it follows the same idea that all relevant assets are represented digitally. This fact of the factory is taken into account in the following concept by choosing a modular approach in which each resource and product has an AAS. These individual representations provide the DT with asset-specific information. This information is then available in a distributed form and can be maintained by those responsible for the assets. This also allows individual factory components to be replaced at any time without the need for major changes to the factory model. Starting from the life cycle of the production system, which begins with engineering, the parallel development of the DT of the factory also begins. Once the resources have been selected, the digital representations, in this case, the AAS of the corresponding assets, can provide information about these resources. Ideally, the AAS is already set up by the machine supplier and is part of the machine delivery, and will be complemented if changes arise. In the factory, this AAS is integrated into the process and manages the machine in the factory system, including the documentation of the operation by storing process data. The product to be manufactured also receives a corresponding AAS in production, which can already contain relevant information in product creation and is now expanded by the process information in production and will then be delivered as part of the product. The AAS thus forms the interface to the physical world. This is performed, on the one hand, by the basic digitally stored description of the physical asset, which records the current state of an asset in each case with the help of sensor values. On the other hand, the AAS also offers the possibility to communicate with the physical elements of the digital world and to influence their state by control commands. Therefore, the concept can be seen as an enabler for the digital factory.

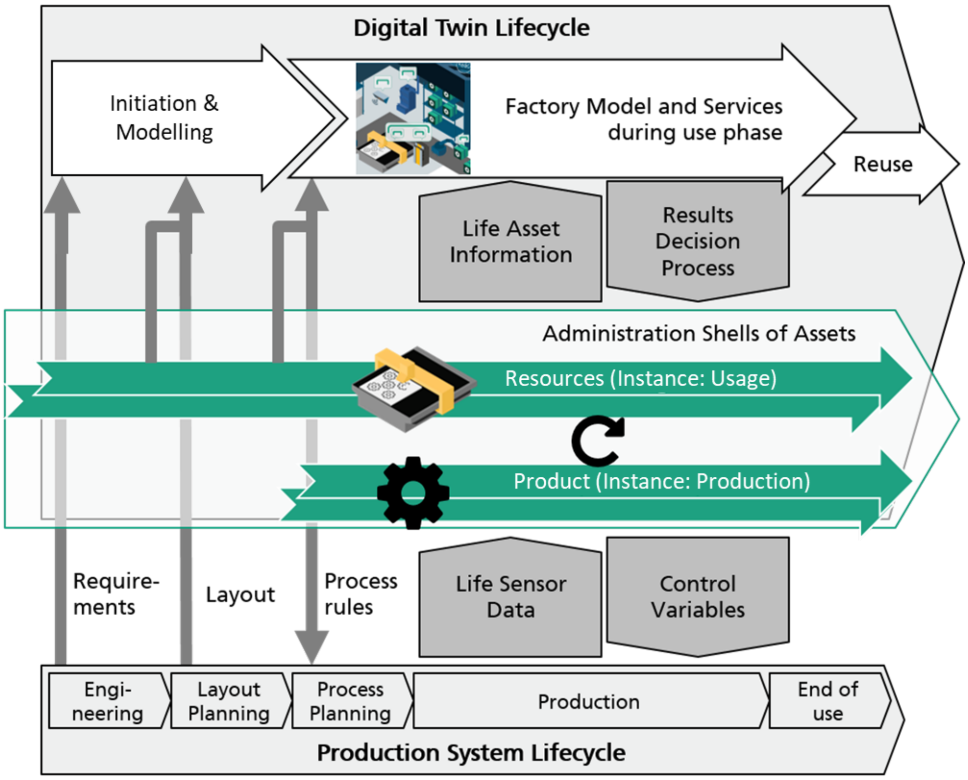


Figure 5. Lifecycle model for modular digital twins, where asset-specific information is modeled in asset administration shells (AASs), and asset interaction is modeled in a factory model (source: own illustration based on Ref. [7]).

The factory model, which turns the concept of a digital factory into a digital twin concept, is composed of individual models. Modeling effort is required here, but the information from the individual resources can already be accessed so that only the interrelationships need to be entered. Creating individual digital representations for each asset is much easier to handle in terms of complexity than for an entire factory system. The advantage is also that the manufacturers of the assets can already represent the basic data and behavior of the resource itself, and the operator can simply extend this with the data relevant to them.

As described, the concept is based on the derived considerations, elements, and conditions given in Section 3 and also by Stark and Damerau [7], who consider the DT in its life phase, as well as the considerations that are in the RAMI 4.0 reference architecture. Although the latter is intended for the concrete implementation of industrial applications, it is ultimately only a reference architecture. The concept is therefore to be concretized on the basis of the requirements given in Section 3 and checked for its ability to be implemented. To fulfill the derived requirements and conditions of a DT given in Section 3, our concept has the following characteristics:

1. Data and knowledge-based: The AAS provides current information about the resources in each case through an active connection to the physical resource.Due to the system's modular structure, the individual components can be kept up to date with little effort because the management of the resources lies with the respective experts and does not have to be carried out by a simulation expert.
2. Modularization: AAS provides modularization for individual resources. In the case of the replacement of resources, adaptation of the model is easily possible. Only the relationships of the resources to each other must be maintained in a factory model.
3. Light weight: The real-time capability depends on the technologies used but is not prevented by the concept.
4. Hierarchy: AAS offers the possibility to build a hierarchy. In the present concept, the product, the production facilities, and the factory model can already be called hierarchy levels. However, any units, e.g., production areas, can also be formed.
5. Standardization: The concept is based on DIN SPEC 91345 [8], which also includes the AAS. The AAS can be seen as a regulation that can work with standardized information models, etc. In addition, there are currently further standardization efforts in this area. It is crucial that modelers adhere to the existing standards.
6. Servitization: The use of standard services is highly dependent on the implementation of the factory model and the technologies used. The AASs on the resource level enable the standard protocols during communication and are therefore an enabler of a service-oriented architecture.
7. Openness and scalability: Modularization at the resource level enables easy extensibility of the model. Only the integration into the factory model depends on the concrete implementation and determines the effort required to integrate additional resources. The AAS is operated as an open-source project, so the work can be accessed here.
8. Robustness: This aspect must be considered, especially during implementation.

5. Conclusions

This paper first shows the need for a unified understanding of the requirements for the meaning of the term digital twin. This represents a central tool in the context of digital production. We show that there is no uniform definition or description of this term within the research community. This leads to the fact that the requirements which are derived from it are not clearly formulated. This gap is closed by the authors in this paper. Through a literature research, different definitions and descriptions of the term digital twin are classified and compared. From this, common properties are identified, which represent the essential requirements. Finally, an approach embedded in the RAMI 4.0 model is used to demonstrate how these derived requirements can be implemented. This enables the sustainable and scalable use of a DT in the context of digital production. The digitized production is an essential component and central element for future production to produce sustainably, flexibly, and efficiently. For example, further research must show how efficient modeling is possible for specific submodels, e.g., efficiency and flexibility models for production. In doing so, care must be taken to ensure that the requirements presented are met. The work dealt specifically with the life cycle and the higher-level architecture. RAMI was placed at the center of the consideration, and the agreement of an understanding for the digital twin and RAMI was considered. A comparison with other reference architectures, such as the industrial internet reference architecture (IIRA) or smart grid architecture model (SGAM), was left out. In the next step, however, it is appropriate to go deeper into the analysis and look more closely at the individual components of the architecture.

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