Digital Twin Paradigm Shift: The Journey of the Digital Twin Definition

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Abstract: This paper examines the paradigm shift in the definition of the digital twin in recent years and describes how the definitions differ from each other. After an extensive literature review and the development of a concept matrix, it became apparent that a paradigm shift is taking place from the classic three-dimensional definition – physical and virtual space with a bidirectional connection – to an expanded five-dimensional definition – data and services as extended dimensions. In particular, the focus and developments in Information and Communication Technologies lead to the recognition of the dimensions of data and services as an independent dimension. In addition, further descriptions of the concept of the digital twin were assigned to the known dimensions.

1 INTRODUCTION

By combining real and virtual space, new applications are emerging that lead to higher and more uniform production and quality (Grieves 2014). Due to the many possible applications, the concept of Digital Twins (DT) receives a lot of attention in many different fields in research and practice (Zhao et al. 2019a). Since its introduction in 2003, the concept has steadily gained interest, and, especially since 2017, the number of annual publications has increased exponentially (van der Valk et al. 2020). In the future, the DT will gain an important role in the industry. Especially through the advances in information technology (new IT), such as Cloud Computing, Internet of Things (IoT), Big Data, and Artificial Intelligence (AI), the merging of the digital and real-world is gaining influence (Tao et al. 2019).

The theoretical foundations of a DT steam from different disciplines, such as information science, production engineering, data science, and computer science (Tao et al. 2018b). Thus, the term DT is used in many areas of scientific literature, for instance, in information science, production engineering, data science, and computer science, as well as in industry. However, this usage is often divergent (Dahmen and Rossmann 2021; Kritzinger et al. 2018). The literature has also not yet provided a clear definition of the construct (Negri et al. 2017; Dahmen and Rossmann 2021). Most definitions mention comparable characteristics, but no unified definition is available. To this end, most definitions show great differences (van der Valk et al. 2020), which in turn can be attributed to the variation in the fields of application (Dahmen and Rossmann 2021; Schleich et al. 2017). It can therefore be concluded that there is currently no uniform understanding of the concept of digital twins (Cimino et al. 2019).

In general, it is very interesting to gain a deeper insight in how digital twins are defined and which definition is used to be more common. Hence, in this paper, we aim to answer the following research questions (RQ):

RQ1: Which definitions of Digital Twins are the most commonly used?

RQ2: How do the definitions of Digital Twins differ?

In the following, chapter 2 describes the methodology and the research design. In chapter 3, we provide the results. In section 4, we discuss the

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development and results of the concept matrix. Whereas in chapter 5, an outlook shows further implications.

2 RESEARCH DESIGN

We use the methodological guidelines of Vom Brocke et al. (2009) and Webster and Watson (2002) to conduct a literature review. According to Vom Brocke et al. (2009), a literature review consists of five steps – publication specification, topic conceptualization, literature search, literature analysis, and revision. First, we specified the publications, i.e., they have to be published in a journal, as conference proceedings, as a book chapter, or as a report. In terms of the topic conceptualization, the publications should contain the concept of the DT as a central element to be included in the study. Furthermore, we used the databases *Science Direct*, *Scopus*, *IEEE Xplore*, and *Digital Library* with the keywords "digital twin", "digital twin application", and "digital twin service". To keep the quality as high as possible, we examined the selected articles for their relevance. We also applied a backward and a forward search. Since the DT covers an interdisciplinary field (Schleich et al. 2017; Tao et al. 2018b), one has to investigate adjacent topics (Webster and Watson 2002). Thus, we conducted a deeper review in information science, production engineering, data science, and computer science.

The review resulted in the realization that the basic definitions of the DT used in the examined literature reviews show substantial differences. To generate a conceptual analysis of the DT, we create a concept matrix according to Webster and Watson (2002).

At last, it was important to find out which topics need further investigation and which areas should be investigated in more detail in the future. All steps were run through twice. Thus, the literature base consists of two iterations and reached theoretical saturation.

Due to space limitations, we have not included the conceptual matrix with all 54 references in this paper, but in the sense of transparency and knowledge accumulation, we provide them and our coding results in the form of a concept matrix [1].

3 THE DIGITAL TWIN CONCEPT

3.1 Classic Approach (Three Dimensions)

As the father of the DT, Michael Grieves (2014) introduced an early approach to the DT in 2003, thereby shaping an initial – classic – view of this concept. At that time, digitization was limited, so most product information was collected manually and was often handwritten on paper. More detailed execution of the Digital Twin, favored by advancing digitization, was described nine years later. In a white paper, Grieves (2014) specifies his former concept and describes the DT as a virtual representation of a physical product that contains information about that product. Shafto et al. (2010) extended the description of a classical DT in a NASA roadmap paper. Based on this, Glaessgen and Stargel (2012, p. 7) define the DT in detail: "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic [...] integrates sensor data [...] maintenance history and all available historical and fleet data obtained“.

According to this, a DT consists of three dimensions: (a) the physical product in real space, (b) the virtual product in virtual space, (c) the bidirectional data link.

The bidirectional data link connects the virtual and physical world and delivers data from the physical to the virtual representation and at the same time transports information and management instructions from the virtual representation to the physical (Grieves 2014; Grieves and Vickers 2017).

Driven by technological developments in recent years, the virtual space transformed from an initially simple representation of the real object, mostly consisting of visual attributes (such as dimensions of the product) as well as the technical data, to a multitude of virtual spaces with additional subspaces, each containing or performing specific operations such as modeling, testing or optimization (Jones et al. 2020; Grieves 2014). The real space transmits the collected data to the virtual space, while at the same time, information and processes are transmitted from the virtual space to the real space. Whereby this information can be used profitably to the respective

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[1] https://bit.ly/3H1dJiM

application. This was initially described as a human-related activity, which is often supported by further process control systems (Grieves 2005). Taking this further, new technological developments make an autonomous or automated process control system conceivable (Grieves 2014). The bidirectional connection, especially in the case of real-time synchronization, leads to the fact that the right decisions can be made based on the latest information (Negri et al. 2017). Finally, the virtual space contains the properties, state, and behavior of the real object and consists of models and data that can predict the actual behavior in the operational environment (Haag and Anderl 2018). Figure 1 illustrates the three dimensions of the DT and shows the interaction of the respective dimensions.

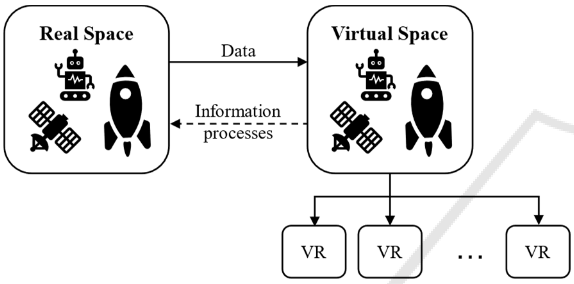

Figure 1: Classic Approach (Three-Dimensional) of a Digital Twin (Grieves 2014).

3.2 Extended Approach (Five Dimensions)

Tao et al. (2019) extend the classic DT by two dimensions and introduce a five-dimensional extended approach (see Figure 2).

The description of the physical entity (1) is comparable to the physical product (a) in real space, as well as the virtual entity (2) is comparable to the virtual product (b) in virtual space. The data collected in the first two dimensions (3) can provide much additional information. All data form the core of the DT (Qi et al. 2018; Tao et al. 2019). This core provides four functions:

First, it reflects the real-world characteristics, behavior, and rules of the physical counterpart, creating an exact duplicate that records all changes. Second, by extrapolation, an ideal action/handling of events can be inferred. Third, by prediction, the cause of problems can be eliminated before they occur, and fourth, an assessment of performance can be achieved beforehand (Tao et al. 2019).

Further, a seamless connection of the individual dimensions (4) represents a critical point because it is indispensable that all information is transmitted. In this context, the individual connections can be optimized iteratively. Here, the various connections can be accessed independently and thus can be controlled, edited, or modified as desired. These connections are comparable to the bidirectional data connection (c) of the classical view of the DT but cannot be equated due to a large number of individual connections (Tao et al. 2019; Tao et al. 2018a; Tao et al. 2018c). The fifth dimension is defined as the resulting services. More precisely, this refers to the assessments, optimizations, predictions, and validations via a user-defined interface. This also allows authorized people, or employees, to take advantage of a DT who have little to no knowledge of how it works and what mechanisms are hidden behind the interface (Tao et al. 2019). Through the service dimension, each additional dimension of the DT can achieve a higher value, as this allows each dimension to be used more efficiently. More specifically, Tao et al. (2019, p. 203) describe it as follows: "Combined with the services, the DT will be easier for usage and will generate more acceptable analysis and evaluation results on product design, manufacturing, usage, prognostics and health management [PHM], and other processes.".

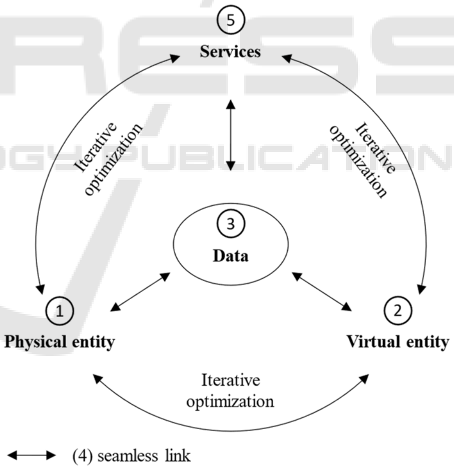

Figure 2: Extended Approach (Five-Dimensional) of a Digital Twin (Tao et al. 2019).

Here, these services do not have to be created or used. Furthermore, services can be divided into resource service, data service, and model service, or according to the product lifecycle, physical unit service, virtual unit service, and data service (Tao et al. 2019, 203 & 208-211).

In general, according to Tao et al. (2018a; 2018c), the DT consists of five equally important dimensions. It is a highly dynamic concept whose complexity can increase during its lifecycle.

3.3 Investigation of Real Applications

With a focus on production systems, Negri et al. (2017, p. 946) define the DT as follows: "The [Digital Twin] consists of a virtual representation of a production system that is able to run on different simulation disciplines that are 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." In most cases, the DT is a model that represents a system while incorporating various levels of simulations (Negri et al. 2017). A DT can be categorized by its area of focus and the technologies used. A digital counterpart to the physical object is identified as the salient commonality. Besides, the integration of data can lead to a different dimension. Here, a distinction is made between the data exchange between the physical and digital counterparts. Some concepts exchange data automatically in real-time, whereas others require manual transfers of data (Kritzinger et al. 2018).

Kritzinger et al. (2018) describe the origin of DT in the reflection of a product or object in virtual space. Furthermore, the main aspect is the ability to provide different information in a uniform format. Here, it was investigated to which extent data is exchanged and how a delimitation can be made. Kritzinger et al. (2018) distinguish between digital model (fully manual data exchange), digital shadow (one data flow automated, one manual), and DT (fully automated data flows).

3.4 Variation or Linking Approach

In 2020, van der Valk et al. (2020) assigned properties to dimensions of the DT. After a literature review of 233 papers, a total of 18 characteristics were derived, which can be divided into eight dimensions. Further, some characteristics may exist in parallel, and some may not ("exclusivity").

The taxonomy developed by van der Valk et al. (2020) was enhanced after a thorough interview series with experts from the industry (van der Valk et al. 2021) and should be seen as a configuration tool for DT. It provides balanced dimensions with associated characteristics of the DT construct. The individual configuration of a DT is highly dependent on the use-case in mind while designing a DT. Therefore, it aims to be a non-specific collection of properties. Nevertheless, certain patterns of commonly used DT configurations are visible, which leads to the conclusion that a very common DT contains a bidirectional data flow, processes data in an identical model of the physical system. It contains human-machine interfaces and machine-to-machine interfaces, receives permanent updates from multiple data sources (van der Valk et al. 2020).

In order to identify the most frequently mentioned characteristics of a DT, Jones et al. (2020) conducted a literature analysis. This revealed a total of 12 characteristics, which describe the DT at its base (Table 1 and Table 2 are provided in footnote 1 above).

4 DISCUSSION

4.1 Comparison of the Definitions

The literature reviews presented in the foregoing illustrate how different the views and understandings of the concepts of DT are. The concepts are used in information science, production engineering, data science, and computer science (Tao et al. 2018b) and are repeatedly described with comparable characteristics and dimensions. The definition and concept of DT is ultimately influenced depending on the target (van der Valk et al. 2020). Further, the concepts are versatile due to the multitude of research and application fields. The overlaps and definitions listed above can generally be compared with each other, which is why comparable statements of individual definitions can be divided into five superordinate areas (see Table 3).

The physical product in real space (a), the physical entity, and the combination of the physical entity (I) and the physical environment (III) can be equated. All three descriptions are to be understood as a physical part, object, or product, which is tangible, i.e., physically existent (Grieves 2005, 2014; Tao et al. 2018b; Jones et al. 2020).

The same approach can be applied to the second dimension. This describes the virtual product in virtual space (b), the virtual entity (2), as well as the combination of the virtual entity (II) and the virtual environment (IV), summarizing as the counterpart of the physical ones. Through certain computer systems, models and simulations can be created in a controlled manner in a wide variety of virtual spaces. In these spaces, different scenarios can be extrapolated, which gain added value, especially by using the virtual environment for optimization, controlling, or control (Grieves 2005, 2014; Jones et al. 2020). Additionally, it should be mentioned that the designation of the virtual environment is determined by the underlying technology, such as database, data warehouse, cloud platform, server, or application programming interface (API) (Jones et al. 2020). In this context, van der Valk et al. (2020) formulated the quantity of model accuracy (D4). This can be classified as either identical or partially identical and represents how accurately the mapping of the real entity with its environment is to be classified as a virtual likeness. A partially identical mapping may result in a smaller amount of data being processed and may therefore be easier to implement but contain the risk of not achieving the desired results. Kritzinger et al. (2018) also introduced a granularity, which focused on the flow of information between the physical and virtual entity (Kritzinger et al. 2018).

The third dimension is the link between the first two dimensions. This is referred to as (c) the bidirectional data link or (4) a seamless link (Grieves 2005, 2014; Tao et al. 2018a; Tao et al. 2018b). Jones et al. (Jones et al. 2020) consolidated separate characteristics for this. These are composed of the (VIII) physical-virtual connection, the (IX) virtual-physical connection, and the (X) twinning, or twinning rate. Comparable characteristics were elaborated by van der Valk et al. (2020). Here, Data Link (D1), Conceptual Elements (D3), and (D6) Synchronization are equivalent to the description of data links earlier (and by Grieves 2005, 2014 and Tao et al. 2018b; Tao et al. 2018a). If either VIII or IX is present, the DT has a one-way connection between the first and second dimensions. After Kritzinger et al. (2017), it can be considered as a Digital Shadow. However, if both connections (VIII and IX) are present, then it is a bidirectional connection and is examined as DT. Here, it is possible to infer from one explanation - of VIII and IX - to the other - unidirectional or bidirectional data connection - and vice versa. If there is a connection, then the conceptual elements will be physically linked to each other. If, again, there is no connection, there is independence between the physical and virtual entities. Similarly, a twinning process (associated twinning rate) exists only if a (VIII) physical-to-virtual connection and a virtual-to-physical connection exist (Jones et al. 2020; Tao et al. 2018b; Tao et al. 2019, p. 4).

Furthermore, this is the basis of synchronization, which cannot take place if there are no connections between the units to be synchronized. In addition, Synchronization (D6) addresses whether continuous synchronization takes place over the course of (work/process) time, i.e., over the course of the product life cycle (van der Valk et al. 2020). This is the essential aspect already addressed by Grieves (2005) and presented as a benefit for PLM. Tao et al. (2018a) also describe accurate synchronization and fidelity to perform real-time analyses that lead to the best possible results. Similarly, Jones et al. (2020) describe (VI) fidelity as an important characteristic of the data link, which translates to the number of parameters, their accuracy, as well as the degree of abstraction that occurs between the virtual and physical twin, or environment. Together, the aforementioned dimensions/characteristics describe the data link between the real space in the real environment and the virtual space in the virtual environment.

Grieves (2014) describes the Digital Twin as a three-dimensional construct that includes the

Table 3: Comparison of the presented breakdowns.

three-dimensional construct (Grieves & Vickers)	Extended Approach (Five-dimensions) (Tao et al.)	twelve Characteristics (Jones et al.)	Taxonomy (van der Valk et al.)
(a) the physical product in real space	(1) the physical entity	(I) physical entity (III) physical environment	(D4) model accuracy
(b) the virtual product in virtual space	(2) the virtual entity	(II) virtual entity (IV) virtual environment	
(c) the bidirectional data link	(4) a seamless link	(VIII) physical-virtual connection (IX) virtual-physical connection (X) twinning, or twinning rate (VI) fidelity	(D1) Data Link (D3) Conceptual Elements (D6) Synchronization
	(3) collected data	(V) parameters (VII) state	(D7) data input
	(5) resulting services	(XI) physical process (XII) virtual process	(D2) purpose (D5) Interface

elements explained above. Unlike Tao et al. (2018a), he did not refer to the data collected, processed, or generated by the DT as a separate dimension. However, there is a fluid boundary or transition. Tao et al. (2018a) describe that the (3) collected data leads to a continuous improvement in self-development, as the data is exchanged between the first two dimensions automatically and in real-time (here, an ideal case is assumed, which define the dimensions described in advance). Furthermore, data is presented as the central element of the DT. They built the core and have data connections to each associated part (Tao et al. 2018b). The data lying in it is referred to as (V) parameters by Jones et al. (2020), which characterizes the nature of the data, its information, and the processes that occur between the real space in the real environment and the virtual space in the virtual environment. In addition, the (VII) state addresses the current values of the measured parameters (Jones et al. 2020).

According to van der Valk et al. (2020), the data input (D7) can come in as raw data, e.g., directly from sensors or as already processed data. In the big picture, these are different ways to characterize the data within the DT. Here, the processed data can come from a physical (XI) or virtual process (XII). This is defined by the foreseen purpose (D2) of the DT. The purpose can ultimately include various services that can improve the convenience, reliability, and productivity of a technical system, among other things (Tao et al. 2018b). Such a service can be transmitted via IoT, from machine-to-machine interfaces (M2M), or be carried via human-to-machine interfaces (HMI), which can perform further work steps (van der Valk et al. 2020). The interface (D5), in turn, displays the state of the data or parameters and can provide a service by highlighting changes in the data. Overall, the services of the DT are very versatile and can therefore not be easily concretized, which is why the two dimensions around the data and services are characterized by a smooth transition.

4.2 Concept Matrix

In order to identify which definition is most frequently used, a concept matrix was created. Due to the limited space, the concept matrix is provided through the above link.

The DT is a complex model that is a digital copy of various entities and can be extended arbitrarily and independently of other entities. Additionally, it is automated and globally available in real-time (Aivaliotis et al. 2019). Among other things, this can create a high level of transparency (Kampker et al. 2019). This can lead to significant advantages in the development, production, maintenance, and servicing of products, especially in the case of complex products such as aircraft or electrical systems, manufacturing, and supply chain management (Tao et al. 2018a). Fittingly, Enders and Hoßbach (2019, p. 7) define the DT as follows: "A Digital Twin is a virtual representation of a physical object called a Physical Twin. The Physical and the Digital Twin may be connected to each other. A Digital Twin can provide more information about its Physical Twin than the Physical Twin itself can provide." In the literature review, the two authors referred to the classic approach of the DT. The result of the investigations of the concept matrix shows that this is the most widespread and thus most common view of the DT. Here, the definition according to Grieves (2014) describes a total of three dimensions that make up a Digital Twin. At 37.04%, more than one-third of the articles studied use this definition as the foundational knowledge for the DT. Almost a similar number of articles (35.19%) use the definition of Glaessgen and Stargel (2012). This definition does not use specific dimensions but describes a DT with some characteristics that are to be valued in general and used especially in the context of spaceflight. Since the Digital Twin has its origin in NASA's Apollo missions, this is a popular reference point for many authors. The third most referenced definition, at 33.33%, is that of Tao et al. (2018a, p. 3566). This describes a total of five dimensions and was explained as the extended approach. In this view of the DT, the focus is on Data and is further expanded by the services.

In the previously described determination of the most common definitions, the frequency of citations was implied as to the basis. If the data are now adjusted with respect to publication years, the result is in a slightly different order. The reason for adjusting the order is as follows. An article published in 2018 cannot have been referenced as basic knowledge in a paper from 2015, so it may not be relevant for the percentage calculation. In the adjusted order, a trend towards the extended approach of Tao et al. (2018a) of the DT can be identified. Although it can be criticized that a lower total number of contributions in the calculation leads to a higher, percentage share, over the years the interest in the construct of the DT increased more and more. Furthermore, constructs such as for data generation, Big Data, data mining, etc., are becoming more and more in focus (Tao et al. 2019, p. 19; Qi et al. 2018). Therefore, an overall trend can be identified, which puts data at the core. At 66.67%, more than half of the published contributions as of 2018, take their foundational knowledge from Tao et al. (2018a). Furthermore, 40.82% also use the classic approach according to Grieves (2014), and 38.00% the definition is referring to Glaessgen and Stargel (2012).

Thus, it is evident that there is an evolution in the construct of the DT. From the classic three-dimensional approach according to Grieves (2014) to an extended five-dimensional view according to Tao et al. (2018a). Furthermore, it can be noticed that technological developments allow a DT to take on different sizes. On the one hand, it can be a single small component, and on the other hand, it can represent an entire production line, with different sizes and elements, even a complete supply chain. This leads to the dissolution of previous limitations and expands the possible applications (Qi et al. 2018, p. 238). This brings the general definition, according to Boschert and Rosen (2016), back to the forefront, allowing the construction of the DT to be applied in many areas. The authors refer to the product lifecycle (PLC) and define: "The vision of the Digital Twin itself refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all - the current and subsequent - lifecycle phases." (Boschert and Rosen 2016, p. 59). In each phase of the PLC, more data is generated that represents one's own state as well as the state of the environment (Boschert and Rosen 2016; Haag and Anderl 2018). The underlying idea of the DT is that it should act as an information construct via the PLC (Grieves and Vickers 2017).

Finally, by shifting the perception of the DT from the classic approach of Grieves (2014) to the extended approach of Tao et al. (2018a; 2018b), the focus is primarily on data. This concept can ensure information availability and traceability across lifecycle phases (Ströer et al. 2018). By having data at the core (Qi et al. 2018), increased services can be provided throughout PLM (Tao et al. 2019, p. 11). Through intelligent data integration and data processing across all product lifecycles, the DT can lead to increased performance of the product, or processes, in the physical space (Qi and Tao 2018).

5 CONCLUSIONS

This paper reviews different definitions and influence streams of digital twins in the literature. From this database, mainly influenced by information science, production engineering, data science, and computer science, we have shown that there are three streams of literature that coin the different types of definitions (RQ1):

- the classic approach – following Grieves (2014) and Glaessgen and Stargel (2012) – with physical and virtual products, as well as data flows
- the extended approach – following Tao et al. (2019) – who extends the classic approach by services and collected data
- the applicational approach, which forms its definitions by the portrayed use cases

To summarize, the most used definitions are in descending order: Grieves (2014), Glaessgen and Stargel (2012), and Tao et al. (2019).

To answer RQ2, a concept matrix was developed. It provides an overview of the differentiation between the definitions. Certainly, the development of recent works shows a divergence towards more complex and more detailed definitions and supports the extended approach. Additionally, the definition of DT develops likewise technological improvements are made and adapt to the requirements of the user.

Our work is subject to certain limitations. As the analysis of the literature base is influenced by subjective decisions, other researchers might define different scopes and, hence, might gain other results, especially with regards to other domains.

This paper provides several contributions. As scientific contributions, this paper analyzes definitions and streams which influence them through a thorough review. It provides a deep insight into the explanation of digital twins and contributes to the knowledge about digital twins. This brings the opportunity for researchers and furthermore managerial contributions for practitioners to fully understand the field of digital twins.

As possible further research, the more and more common real-world applications are worthy for a deeper analysis. The comparison between theoretical works and operational facts might provide interesting insights on the implementation of digital twins.

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