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Digital Twin or Digital Model: An Analysis of Definitions along the Product Lifecycle

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Abstract

Digital twins are a prominent topic in data-driven design thanks to advances in the Internet of Things. Due to the high number of publications and the resulting definitions, the differentiation between digital models and digital twins is not always clear. Therefore, this paper aims to refine the boundaries between digital model and digital twin through an analysis of various definitions according to common digital twin characteristics. A classification of case studies along the product lifecycle further highlights the differences between the definitions. The overall goal of this paper is to enhance communication and efficiency in the use of digital technologies by providing the difference between digital model and digital twin.

Keywords: Digital Twin; Digital Model; Product Lifecycle

1. Introduction

Digital twins (DT) are still a trending topic in research, as shown by the growing number of publications [1]. These growing numbers have led to various definitions of the DT, which is why it is not always clear what distinguishes a DT from a digital model (DM). Consequently, due to the confusion surrounding the terms, companies seeking to leverage the various benefits of DTs often misuse the term [2,3]. This misuse could lead to people rejecting the DT as just a hype and prevent them from achieving the maximum potential of the DT concept [4]. Therefore, this paper looks at the different definitions and applications of DTs and aims to clarify the difference between a DM and a DT.

2. Current discussion on definitions

Initially formulated by Michael Grieves in 2002, the concept of the DT has since been given numerous definitions. NASA first defined the DT in 2012 as “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” [5]. However, even at this early stage, there were notable differences from Grieves original description. According to Grieves, a DT does not necessarily require a pre-existing product [6], whereas NASA's definition focuses on an as-built product. Grieves argues that this over-specifies the twin metaphor, the intention to realize a physical product is

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sufficient [6]. However, this perspective causes the boundaries between DT and DM to become less distinct.

By DM we do not refer to the definition according to Kritzinger [7], which relates to the degree of automation of the physical and virtual entities connection. Instead, by DM, we speak of any digital representation of a product that does not necessarily exist yet, such as a CAD model, simulation or database.

Contrary to Grieves, Wright et al. state "A digital twin without a physical twin is a model" [4]. They identify the main strength of the DT in the ability to provide an accurate description of an object that changes over time, while a DM can only provide a snapshot at a specific moment [4]. Stark et al. also differentiate the DM from a DT. According to them, a DT designates all DMs that can be used to reflect the function and behavior of a unique physical product in use [8]. Wilking et al. identify the main difference between the DT and the virtual prototype in another aspect. They see the difference in the ability to receive data from use and derive recommendations for action for the user [9]. In doing so, they look at the data relationship between the physical and the virtual entity, which is often described as bi-directional in the case of a DT but is not always included in the definition [10]. Jones emphasizes that it is possible to have a DT with only a uni-directional relationship from physical to virtual entity, although this offers no advantages. According to him, the continuous loop, which involves an action based on the simulations of the virtual entity, is the difference to the classic DM [10]. These various statements show that there is no uniform opinion as to what distinguishes a DM from a DT.

However, many authors agree that the DT can have advantages in several phases of the product lifecycle [6,8,11–14]. One example from the design phase is the use of technical inheritance to feed the data collected by the DT back into the product lifecycle [12,15,16]. In the production phase, the DT can be used to optimize the manufacturing process [17]. The DT can then be used, among other things, to control the product in the use phase or to perform predictive maintenance. During the End-of-Life phase, the information gathered by the DT can be used to decide on the reuse of the product [12], for example, recycling or remanufacturing, in order to increase ecological as well as economic sustainability through DTs [18].

3. Methodology

To answer the question of how DT and DM differ from one another, suitable questions for examining the various definitions of the DT are defined on the basis of Jones characteristics (see Sec. 4.1 for the definition of the questions). In the second step, the definitions of various authors are examined based on the questions derived from the characteristics. For this step, the statements of Grieves et al., Stark et al. and Tao et al. are examined, as these are frequently cited authors in DT research and receive special mention in [10]. Based on the results from the conducted analysis of the definitions, several case studies along the product-centric product lifecycle, which are labeled as DT, are analyzed. Each case study gets examined whether it qualifies as a DT according to the respective author. The case studies for the respective product lifecycle are drawn from the research of Jones and Pronost [10,19]. Based on abstract screening, non-engineering examples and paradigms or similar are excluded, as the focus should be on clearly described application examples from the engineering sector. If, based on full paper screening, more than three examples are suitable, use cases with different characteristics are chosen to emphasize the differences in the authors definitions. Based on the results of the analysis of the definitions and the case studies, a concluding statement is made on the difference between DT and DM.

4. Results

4.1. Selection of the evaluation criteria

Jones identified 12 core themes as the characteristics of a DT, which are the basis for the evaluation criteria in this paper. Of the 12 characteristics, 7 are eliminated due to being redundant or assumed for the classification of whether the application example is a DT or not, so that only the critical characteristics are considered (see Tab. A1). The fidelity of the DT, for example, is not considered, as the aim is not to assess the maturity of the DT but to determine whether the application example satisfies the criteria for being classified as DT.

Physical entity (C1), described as a real-world artifact [10], is the first relevant characteristic (see Fig. 1). From this, the question is derived as to whether a physical entity has to exist for the application example to be a DT. The existence of a virtual entity is assumed in this paper, as it presupposes the principle of differentiating between a DM and a DT.

Physical*-to-virtual connection (C2) describes the connection from the physical to the virtual environment and is based on physical metrology [10]. Here too, the question arises as to whether, according to the authors, this connection has to be present for the application to be a DT.

*Since a physical entity does not necessarily have to exist based on C1, it is analyzed here whether there needs to be a data flow from the entity to be twinned (regardless if it is physical or not) to the virtual entity.

Virtual-to-physical* connection (C3) describes all data flows from the virtual to the physical environment [10]. Similarly to C2, it is questioned whether the authors believe that this connection has to be present for an application to be considered a DT.

State of the virtual entity (C4) concerns another critical characteristic. The question here is whether the virtual entity reflects the current state of the physical entity or whether the virtual entity can also carry out adapted what-if simulations.

Twinning rate (C5), which describes the frequency with which the physical and virtual entities are synchronized [10], is another relevant characteristic. This characteristic raises the question of the frequency at which the exchange has to take place, according to the authors, in order for the application to qualify as DT.

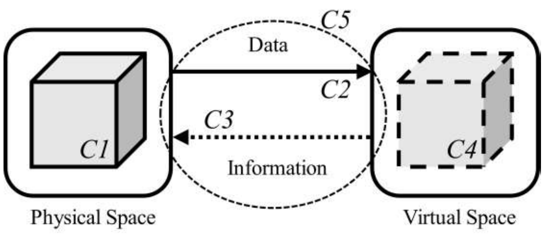

Fig. 1: Chosen characteristics (CX) labeled in digital twin model concept based on [6].

4.2. Analysis of definition according to the evaluation criteria

As described in the methodology (see Sec. 3), only the definitions of Grieves, Stark and Tao are considered. These authors make contradictory statements on the existence of the physical product (C1). Tao et al. mention that a physical model has to be contained in the DT [11]. Grieves, on the other hand, states that a DT has to contain an actual or intended physical element that currently exists or will exist [6]. Stark mentions, among other things, an intangible asset as an example of an entity to be twinned, which implies that the entity doesn't have to be physical. In contrast to Grieves, however, it must be an active product instance, so an intended product is not sufficient.

The next question is how the connection between the entities has to be developed for a DT to exist (C2 and C3). According to Stark, the connection between the entities must have a meaningful linkage but must at least be uni-directional [8], i.e. information must be transmitted to the virtual entity by sensors, but a connection from the virtual to the physical entity does not necessarily have to be present. Tao states that the difference between a classic CAD model and the DT is the two-way interaction [11]. This means that there has to be a bidirectional connection between the entities. Grieves states that a DT must contain a communication channel between the physical and virtual entity and also depicts a flow of information from the virtual to the physical model in the illustration [6]. However, since no product needs to exist corresponding to his definition, it is concluded that both the virtual-to-physical* connection and the virtual-to-physical* connection do not necessarily have to be present.

The next characteristic to be examined in this paper is the state that the virtual entity represents (C4). Since Stark notes that the DT is a digital representation of an active unique product [8], it can be assumed that what-if simulations do not correspond to his definition of the DT. Tao et al. mention that the DT is a real mapping of the physical entity [11], so what-if simulations do not fit within his definition of the DT. Grieves, on the other hand, defines the DT Prototype, where the product is created and tested in the virtual before it is produced [6]. Accordingly, applications in which a what-if simulation is carried out also qualify as DT according to his definition.

The last question concerns the twinning rate between physical and virtual entities (C5). Tao describes the DT as a real-time digital representation [11], emphasizing the need for real-time connection between the virtual and physical entity. Stark's 8-dimension model suggests that the update frequency can range from weekly to real-time [8], according to this definition, the twinning rate does not necessarily have to be real-time. Grieves, on the other hand, makes no statement about the twinning rate of the entities. The results visualized in Figure 2 show that the authors statements on the characteristics of a digital twin differ.

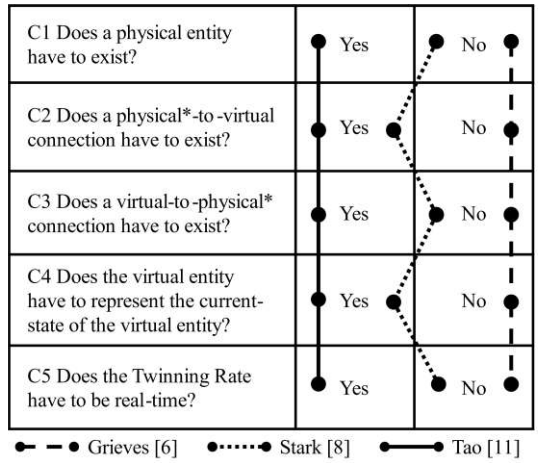

Fig. 2: Examined authors statements on the characteristics of the digital twin. *For explanation see Section 4.1.

4.3. Application of the evaluation criteria to the use cases

As written in Section 3, three case studies from each product lifecycle phase were chosen, which are referred to as DTs by the authors of these case studies. Based on the three statements of the authors Grieves, Stark and Tao regarding the characteristics, the case studies are either classified as DT if they fulfill all characteristics according to the respective author or as DM if they do not. Results are shown in Table 1.

Table 1. Case studies classified as digital twin or digital model according to the respective author.

Life cycle phase	Case study	Grieves	Stark	Tao
Design	[20]	●	C2	C1
	[21]	●	C2	C1
	[22]	●	C2	C2
Production	[23]	●	●	●
	[24]	●	●	C3
	[25]	●	●	●
Use	[26]	●	●	●
	[27]	●	●	●
	[28]	●	C4	C4
End-Of-Life	[29]	●	C4	C4
	[30]	●	●	C5
● Case study qualified as digital twin		CX Case study qualified as digital model, including the first missing character		

As seen, the contradicting definitions carry over to the application examples. According to Stark and Tao, there is no DT for the design phase. For Tao's definition, this is the case because a physical product does not yet exist in two case studies [20,21]. Similar, for Stark, these cases don't qualify as DT, as they don't include an active product, therefore no physical*-to-virtual connection exists. In one case [22] the application doesn't qualify as DT for both due to the fact that no data is transferred from the physical product to the virtual one. Instead, the same inputs are given for the virtual entity as for the mechanical entity and the virtual entity is adapted on the basis of these values. Likewise, in this application example, there is no feedback loop to the physical product. According to Grieves' definition, which only requires an intended product, all application examples qualify as DT.

Since the product lifecycle is considered product-centered, no examples representing a DT of the manufacturing machine were used for the production phase. Instead, case studies are chosen, which consider the product being manufactured as physical entity. In this PLC phase, all examples qualify as DT according to the authors definitions, except for one example [24] in which there is no return flow from the virtual entity.

In two cases [26,27], the application examples from the use phase are a DT according to all definitions. In one case [28] it is only a DT according to Grieves, as the virtual entity is a what-if simulation that is carried out on the basis of historical data. Accordingly, although there is an active product and a bidirectional data connection (virtual to physical indirectly through design decisions), it is not a DT according to Stark and Tao. The fact that there is no real-time twinning is an additional argument against the definition of Tao.

For the end-of-life phase, there are only two case studies that mention the DT in an application. In one application [29], a CNC machine is virtually reconditioned on the basis of the BOM and then emulated. Since the virtual entity does not represent the current state, it is not a DT according to Tao and Stark's definition. In the second application example [30], the status of a product is transmitted by the user to a server, on the basis of which a decision is made on how to handle the product (recycling, discarding, etc.). According to the five established criteria under Grieves' definition of the DT, this example qualifies as a DT. According to Stark as well, although the twinning rate is not real-time. According to Tao's definition, this is the reason why this example is not a DT.

5. Discussion

To address the underlying question of what distinguishes a DT from a DM, the results from Sections 4.2 and 4.3 are discussed. The findings show that Grieves' definition of the DT is very broad and therefore, all case studies are considered a DT according to his definition. The biggest difference to Tao and Stark is that even a simulation of an intended product is considered a DT. However, this merely renames a technology that has already existed for years, which means that DT does not reach its full potential [4].

Tao's definition of DT is the narrowest. In contrast to Stark, the product has to be physical, the connection between the physical and virtual entity must be bi-directional and also real-time. As already written in [3], a uni-directional relationship (physical to virtual) does not result in an essential advantage, but the state of twinning is reached. This state can be understood as an earlier stage in the development of a value-adding DT, but it is already clearly different from a classic DM.

A real-time connection also maximizes the advantages of the DT, but a real-time connection is not possible in every application. For example, in aerospace, signals cannot always be sent in real-time, although a DT can still be of great benefit in this application [31].

The authors of this paper interpret the main difference between a DM and a DT as the transfer of data from an active entity to a virtual entity in order to represent the current state of the active entity in the virtual entity.

Examining the examples distributed across the PLC reveals that, according to Tao and Grieves, none of the examples in the design phase correspond to a DT. Only if a DT of an active prototype is created the application can be qualified as DT in this phase according to the definitions of these two authors. In the production and use phase, there are several examples that are DTs according to the authors Stark and Tao, which is where the DT concept has the greatest impact. For the end-of-life phase, only two suitable examples were found in Jones and Pronosts research, only one of which is a DT according to Stark. This shows that, at least in current studies, the DT has no big impact in this phase.

According to these findings, it is not the DT that accompanies the entire PLC but the DM, which has different characteristics in the different PLC phases. It is important to differentiate between the terms in order to avoid dismissing the DT as a hype and to utilize the full potential of the DT.

6. Conclusion and limitations

This research investigated the difference between the DM and the DT because of the uncertainties that exist with regard to the definition. Therefore, suitable questions were derived from common DT characteristics. Next, the definitions of Grieves, Stark and Tao were examined under the derived questions. With the classified statements of the authors, various case studies from each product lifecycle phase were evaluated as to whether they qualify as DT to the according author.

The results showed that Grieves has the widest definition of the three. As long as a product is intended, the DM of this product is a DT. Stark has a narrower definition of the DT. In his opinion, for an application to qualify as a DT, an active product has to exist, which has at least a uni-directional connection to the virtual entity. Tao has the narrowest definition of the examined authors. According to his statements, to qualify as a DT, there must be a physical product that has a bi-directional relationship with the virtual entity being used in real-time. We conclude that the main difference between a DM and a DT is the transfer of data from an active product to a virtual entity that represents the current state of the active entity. This differentiation is intended to prevent the misuse of the term DT and should help the DT concept achieve its full potential.

Although these findings help to understand the difference between DT and DM, limitations need to be addressed. Some of the authors statements offer room for interpretation regarding the derived questions, as they are not all addressed directly in their scientific works. Consequently, the classified statements used in this work do not necessarily correspond strictly to the authors opinions. In addition, the investigation of the case studies along the product lifecycle has no statistical significance and should only highlight the differences in the definitions. In order to make a comprehensive statement about the DT along the product lifecycle, a larger number of case studies would have to be analyzed.

Acknowledgements

Corresponding research data, including used statements of the examined authors and detailed analysis of the case studies according to the characteristics, can be found in [32].

Appendix A.

Table A1: Characteristics with corresponding questions or reason for exclusion based on [10].

Characteristic		Question/reason for exclusion
C1	Physical Entity	Does a physical entity have to exist?
C2	Physical*-to-Virtual Connection	Does a physical*-to-virtual connection have to exist?
C3	Virtual-to-Physical* Connection	Does a virtual-to-physical* connection have to exist?
C4	State	Does the virtual entity have to represent the current state of the virtual entity?
C5	Twinning Rate	Does the Twinning Rate have to be real-time?
C6	Physical Environment	Exists as soon as a physical entity exists.
C7	Virtual Environment	Exists as soon as a virtual entity exists
C8	Virtual Entity	The existence of the virtual entity is required for a distinction between digital model and DT.
C9	Fidelity	The aim is to determine if it qualifies as a digital twin, not assessing its accuracy or maturity.
C10	Parameters	All data types, including human-in-the-loop, are accepted.
C11	Physical Process	Physical Process is a prerequisite for the DT to be meaningful.
C12	Virtual Process	Virtual Process is a prerequisite for the DT to be meaningful.

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