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DIGITAL TWINS IN SIMULATIVE APPLICATIONS: A TAXONOMY

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ABSTRACT

With the advances in information technology, the concept of Digital Twins has gained wide attention in both practice and research in recent years. A Digital Twin is a virtual representation of a physical object or system and is connected in a bi-directional way with the physical counterpart. The aim of a Digital Twin is to support all stakeholders during the whole lifecycle of such system or object. One of the core aspects of a Digital Twin is modeling and simulation, which is a well-established process, e.g., in the development of systems. Simulation models can be distinguished on the basis of different dimensions, e.g., on the basis of their time perspective. The existing literature reviews have paid little to no attention to this simulation aspect of a Digital Twin. In order to address this, the authors have developed a taxonomy based on an extended literature review to bridge the aforementioned gap.

1 INTRODUCTION

Due to advances in information technology, e.g., Big Data and Industry 4.0, and numerous areas of applicability, e.g., manufacturing (Rosen et al. 2015) and logistics (Haße et al. 2019), Digital Twins have gained extensive attention in both practice and research (Zhao et al. 2019) and are considered one of the top ten technology trends (Gartner Inc. 2019). The reader is kindly referred to Enders and Hoßbach (2019), who provide an overview of application domains for Digital Twins. After their comprehensive literature review, they state that simulation is the main application of the Digital Twin.

A consequence of the advances mentioned above in information technology is the rise in the volume of data. Forecasts predict a rise in generated data from 33 zettabytes up to 175 zettabytes by 2025, with 1 zettabyte being a trillion gigabytes (Reinsel et al. 2018). The adequate handling of vast amounts of data is getting increasingly important, especially in the context of production and logistics (Uhlemann et al. 2017). One of the challenges is to prevent the emergence of data silos during the data lifecycle (Tao et al. 2018). The purpose of a Digital Twin is the linking of both the physical and digital world by establishing a digital representation of physical objects or systems (Zhao et al. 2019). Hence, this concept offers a promising approach to tackle the challenge.

Following the definition given by Glaessgen and Stargel (2012), the core element of a Digital Twin is the simulation. During our studies, the wide range of Digital Twins used in simulative applications attracted our attention. However, we noticed that the Digital Twins differentiated among each other. This observation coincides with the findings of Cimino et al. (2019), who describe the multitude of different definitions of Digital Twins. To the best of our knowledge, there is no scientific paper presenting a classification of a Digital Twin in the context of simulative applications. Therefore, we see the absence of a classification of Digital Twins in simulative applications as a promising research gap. As a classification methodology, one can use multiple techniques, e.g., taxonomies, typologies, or ontologies (Bailey 1994). A taxonomy lays the foundation for characterization and is the preferred methodology to structure and classify existing concepts and definitions (Bailey 1994; Glass and Vessey 1995; Nickerson et al. 2013). Therefore, to classify the Digital Twins used in simulative applications, we pursue the following research objective (**RO1**): The development of a taxonomy that represents the key features of Digital Twins used in simulation.

To validate the classification and to match our findings with the concept of simulation, the second research objective (**RO2**) reads as follows: The comparison of the concept of the typical Digital Twin in simulative applications, which we derive from the taxonomy, to the given definitions of simulation and Digital Twins.

The remainder of this paper is organized as follows: In Section 2, we give a brief overview of simulation. Section 3 briefly describes the concept of digital twins and discusses different definitions. Section 4 describes the methodology, while Section 5 discusses the results of the conducted research. In Section 6, we present the conclusion and outlook.

2 MODELING AND SIMULATION

Modeling and simulation are two of the most widely used techniques worldwide for analyzing complex systems, regardless of whether they already exist or not (Law 2015). They have a wide range of applicability, e.g., analyzing supply chains or designing manufacturing systems. Based on the definition proposed by Schmidt and Taylor (1970), Law (2015) describes a system as a collection of related objects that can interact with each other. Models are used to study complex systems. A model is a simplified representation of real-world systems (Banks 1998). Simulation is used if an analytical approach is not sufficient, e.g., because the model is too complicated or it takes too long to find a suitable solution. Simulation models are particular types of mathematical models, which can be analyzed through simulation (Kleijnen 2015). The literature provides multiple definitions of simulation. Law (2015) understands simulation as ”...using computers to imitate, or simulate, the operations of various kinds of real-world facilities or processes”, whereas Banks (1998) describes simulation as ”...the imitation of the operation of a real-world process or system over time”. Shannon (1998) defines simulation as ”the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and evaluating various strategies for the operation of the system”. In this paper, the authors adopt the definition of simulation as defined by the Verein Deutscher Ingenieure (2014):

Definition 1 ”Representation of a system with its dynamic processes in an experimentable model to reach findings, which are transferable to reality; in particular, the processes are developed over time.”

It is clear from all definitions that the essential element of simulation is the model. To classify simulation models, Law (2015) lists three dimensions:

- **Static** and **Dynamic**. Static simulation models are a representation of a system at a certain point in time, or time is not of any interest. If the model takes into account the development of the system over time, it is a dynamic simulation model.

- **Deterministic** and **Stochastic**. Deterministic simulation models do not consider any probabilistic properties, whereas stochastic simulation models take probabilities and, therefore, randomness into account.
- **Continuous** and **Discrete** (with respect to time). If the state of the model changes continuously over time, it can be categorized as a continuous simulation model. Otherwise, if the state changes at certain, separated points in time, it is a time-discrete simulation model. Note that there can also exist a classification of continuous and discrete with respect to the system's variables (cf. Gutenschwager et al. 2017).

In addition to these dimensions, simulated ystems can be differentiated into terminating or non-terminating, where the time horizon is either finite or infinite. Conducting simulation studies requires a targeted approach, usually implemented by using procedural models. Well-established procedural models exist in the literature, e.g., the model presented by Balci (1998) or the model proposed by Rabe et al. (2008), which is widely used in the German-speaking countries. An integral part of every simulation study is the validity and the credibility, especially of the simulation model, throughout the phases of the conducted simulation study (Law 2008). The literature identifies multiple techniques on how the verification and validation of a simulation model can be achieved. The reader is kindly referred to the work of Osman Balci, e.g., in Balci (1998), and of the extensive work of the "Arbeitsgemeinschaft Simulation" (ASIM), published by Rabe et al. (2008) (short English version in Rabe et al. 2009), who have described the structured process of conducting verification and validation in a simulation study, list and categorize multiple different validation techniques, and discuss additional factors such as subjectivity of such techniques.

3 THE ORIGINS AND DEFINITIONS OF DIGITAL TWINS

The first usage of the twin concept can be retraced to the Apollo project, in which NASA built multiple space vehicles. The vehicle on the ground mirrored the vehicle in space and was used for training purposes as well as to simulate solutions for critical situations (Rosen et al. 2015). Iron birds are another usage for the twin concepts, which are physical twins of an airliner. Electrification, hydraulics and flight controls are tested with iron birds before an airliner has its maiden flight. The first introduction of a Digital Twin was made by Michael Grieves in 2002, who introduced a concept for the product lifecycle management (Grieves 2014). Albeit not called a Digital Twin, the concept included everything a Digital Twin contained after his definition (see Definition 2) (Grieves and Vickers 2017).

Definitions 2 to 4 provide an overview of definitions that coin our understanding of Digital Twins:

Definition 2 A Digital Twin "contains three main parts: a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together" (Grieves 2014).

Later on, he defines a Digital Twin as a construct of virtual information that describes a physical object very precisely. The virtual model contains information from a micro to a macro level and integrates current data (Grieves and Vickers 2017). The next definition is poised to be the most common and most cited definition (Karakra et al. 2019):

Definition 3 "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" (Glaessgen and Stargel 2012).

They describe a Digital Twin as realistic as possible with an integration of different data sources like sensors, historical data, and complementary data of a fleet, if available (Glaessgen and Stargel 2012). A more recent definition is given below:

Definition 4 ”[A] Digital Twin consists of three parts: physical product, virtual product, and connected data that tie the physical and virtual product” (Tao et al. 2018).

In an additional definition, they extend their statement and see a Digital Twin with five parts: a physical part, a virtual part, a connection, data, and services (Enders and Hoßbach 2019). The above definitions have in common that a Digital Twin possesses a corresponding physical twin. Equally important is a data connection between both twins. This two-way data connection is seen as the most important difference between a Digital Twin and a Digital Shadow. Following Kritzinger et al. (2018), a Digital Twin is a virtual representation with a fully integrated data flow between the virtual and the physical part, whereas a Digital Shadow only possesses an integrated data flow in one direction. In the context of simulative applications, Rosen et al. (2015) see a Digital Twin as the future of simulation, modeling, and optimization technology (Figure 1).

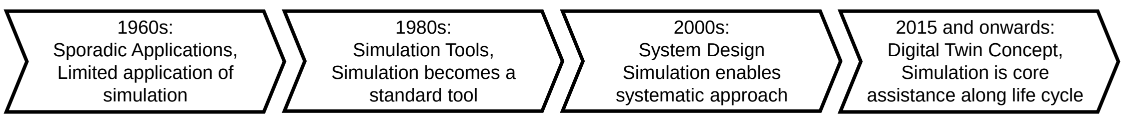

Figure 1: The Digital Twin as the next step of simulation (according to Rosen et al. (2015)).

4 RESEARCH METHODS

In the following, we present our research methods. First, we conducted a structured literature review to gain a saturating literature base. Second, we applied the methodology presented by Nickerson et al. (2013) to create a taxonomy.

4.1 Structured Literature Review

For this research, we conducted a structured literature review according to the five-step methodology described by vom Brocke et al. (2009). As the first step of our literature review, we defined our review scope as publications about Digital Twins in simulative environments. As databases for the search process, we chose AIS eLibrary, IEEE Xplore, Science Direct, and Scopus. We defined a Digital Twin according to the definitions given above (see Definitions 2 to 4), as the second step of our literature review. In the third step, we searched the databases for the search string “digital twins and simulation” with our understanding of simulation, as stated in Definition 1. Our search yielded 170 publications.

Step four contains an analysis of the search results. During the study, we eliminated publications that did not fit our search scope. As exclusion criteria, we applied the following: The search string needs to be part of the title, abstract or keywords, which resulted in 140 publications. Next, we eliminated duplicates and publications that were non-scientific or of low quality. For example, a publication needs to provide a stringent argumentation and must have passed a peer-review process. In the fifth step, we refined the research agenda and focused on publications that deal with objects that follow our definition of Digital Twins in simulative environments. The publication must describe an application or a deepened concept of application of a Digital Twin in simulation. Finally, we conducted a backward search, as proposed by Webster and Watson (2002). The search process resulted in 69 publications, which we took into account for the development of our taxonomy. Since Digital Twins have a wide range of applicability (see Section 1), the 69 papers originate from various domains of applications. The application domains range from engineering and manufacturing (which is the main field of application), software engineering, biochemicals, and disaster relief to applications in health care and hospitals. The literature review showed that most of the Digital Twins are synchronized and share their data bi-directional with their physical counterpart. Furthermore, we followed the guidelines of Cooper (1988) and increased the quality of our structured literature review by the application of valid and persistent procedures during the literature review.

4.2 Designing the Taxonomy

Lambert (2015) explicitly states that a classification of a particular research area is a fundamental step to understand this research area thoroughly. Therefore, we decided to use a taxonomy, because it provides a classification of definitions as well as concepts and, therefore, organizes different concepts (Bailey 1994; Glass and Vessey 1995). We created our taxonomy in accordance with the extensively used methodology of Nickerson et al. (2013). They propose a procedure that consists of seven steps (Figure 2). During the first step, a meta-characteristic has to be determined. This characteristic defines the purpose of our taxonomy. In the second step, one establishes the ending conditions. Nickerson et al. (2013) propose 13 ending conditions, which we decided to follow. As the third step, they recommend a decision on one of two approaches. Generally, they explain two approaches for developing a taxonomy. There is the empirical-to-conceptual approach and the conceptual-to-empirical approach. The first one focuses on the objects, which are examined. In the empirical-to-conceptual approach, a subset of objects is identified (Step 4e), and then these objects are searched for common characteristics, which are grouped together (Step 5e). Lastly, the grouped characteristics are combined into dimensions, which result in a taxonomy (Step 6e).

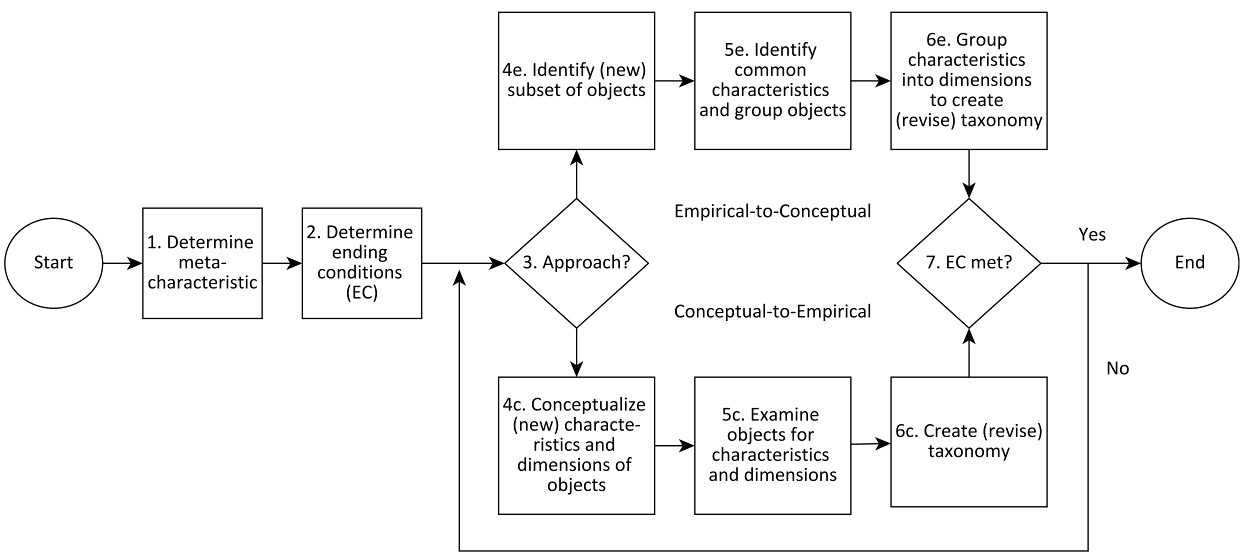

Figure 2: Methodology for developing a taxonomy (according to Nickerson et al. (2013)).

Following the conceptual-to-empirical approach, one has to conceptualize characteristics and dimensions of an object (Step 4c). A subsample of objects is examined for these characteristics and dimensions and the examined objects are sorted into a characteristic (Step 5c). Out of these dimensions and characteristics, a taxonomy is created (Step 6c). Both approaches end in a decision (Step 7). If all ending conditions are met, the methodology ends and the taxonomy is finished. Otherwise, one has to repeat one of the two approaches in an iteration.

5 A TAXONOMY FOR SIMULATIVE APPLICATIONS OF DIGITAL TWINS

As the approach for creating the taxonomy, we chose the conceptual-to-empirical one (Figure 2). Therefore, we first conceptualized the dimensions and characteristics of the taxonomy. For that, we extracted seven dimensions with respective characteristics, which define the concept of simulation. Each characteristic is derived from the state of the art of simulation (see Section 2). For the next step, we considered the 69 publications found in the structured literature review (see Section 4.1). For the first iteration, we examined 35 out of the 69 publications. During this first revision of the taxonomy, we confirmed the dimensions and characteristics identified in the literature (see Section 2). To validate our design of the taxonomy, we conducted a second iteration using the remaining 34 publications. We will introduce the dimensions and characteristics in the following section, starting with the meta-characteristic.

5.1 Meta-Characteristic, Dimensions, and Characteristics

The meta-characteristic defines the purpose of the taxonomy. In accordance with the research question stated above (see **RO1**), the meta-characteristic is as follows: “Properties and elements of Digital Twins used in simulative applications”. Thus, every dimension and characteristic has to provide input on an element or property that defines a Digital Twin that is specifically used in simulation. As stated above, we decided on seven dimensions with numerous characteristics (for an overview of the complete taxonomy with all dimensions see Table 1). In theory, six dimensions are mutually exclusive, while one dimension can address multiple characteristics at the same time. In the following, we discuss every dimension (D_m) and its characteristics (C_{mn}).

Our first dimension is progress in time (D_1). A simulation model can progress in a continuous (C_{11}) time flow or in discrete (C_{12}) steps (see Section 2). The progress in time is a vital distinction of simulations. Thus, it is a very important dimension for our taxonomy. At the same time, the progess in time is equaly important within a Digital Twin. As real time data processing is very important for a Digital Twin (Tao et al. 2018), it is not specified whether this real time processing means a continouos or discrete time flow. An example of a continuous Digital Twin provide Yun et al. (2017). Amongst others, Schluse and Rossmann (2016) describe a discrete Digital Twin. The progress in time is mutually exclusive.

The next dimension deals with probabilities (D_2). A simulation can be deterministic (C_{21}). Thus, it does not contain any probabilities. Alternatively, it can include stochastic probabilities, i.e., random inputs (C_{22}) (see Section 2). As Digital Twins can be described as simulation models (see Definition 3), probabilities are equally important within Digital Twins. Moussa et al. (2018) show a Digital Twin that does not include probabilistic inputs. A stochastic Digital Twin can be found in the works of Guerra et al. (2019). A Digital Twin is either deterministic or stochastic. Hence, this dimension is mutually exclusive.

The third dimension is the model character (D_3). We divide a simulation model into two categories. Either it is a static model (C_{31}), in which a system is represented in a fixed state of time, or it is a dynamic model (C_{32}). van der Valk et al. (2020) show that the model is a vital part of a Digital Twin. It can be an exact copy or an abstraction of the real world model. However, it is not specified, whether the model is static or dynamic. An example of a Digital Twin with a static model can be found in Dröder et al. (2018), while Bilberg and Malik (2019) describe a dynamic model. The dimension is mutually exclusive.

The fourth dimension is the usage of a process model (D_4). We analyze, whether a process model was used to implement the simulation model. Either a model was used (C_{41}) or not (C_{42}). Therefore, this dimension is mutually exclusive. We counted both the implementation based on a procedure model which is established in science (see Section 2) as well as contributions showing a structured and target-oriented procedure or approach, for example, based on successive phases. An example of the usage of a process model provide Martinez et al. (2018). We see the usage of a process model as very important for the development of any digital artifact. Therefore, it is a vital part of the taxonomy.

As the fifth dimension, we determine the scope of the simulation models (D_5). These models might only contain a single entity (C_{51}), as can often be seen when using agent-based simulation or multiple entities. Otherwise, they can represent a system with mutually interacting elements (C_{52}). The same applies for Digital Twins. They can either represent a single entity or a whole system. This dimension is mutually exclusive. An example for a single entity provide Orive et al. (2019), while Pileggi et al. (2019) give an example for a system.

Dimension six refers to whether a verification and validation of the simulation study was conducted (D_6). The dimension is dichotomous, as a verification and validation was either conducted (C_{61}), or not (C_{62}). An example for a fully conducted verification and validation give Bilberg and Malik (2019), while Macchi et al. (2018) did not review their Digital Twin. This dimension is mutually exclusive.

The final dimension is the time horizon (D_7). As shown in Section 2, a simulated system can either be terminating (C_{71}) or non-terminating (C_{72}). Guivarch et al. (2019) show a terminating system, while Cimino et al. (2019) describe a non-terminating one. This dimension is mutually exclusive.

Table 1: Final taxonomy of Digital Twins in simulative applications.

Dimension	Characteristics	
Progress in Time	Continuous (16%)	Discrete (67%)
Probabilities	Deterministic (28%)	Stochastic (72%)
Model Character	Static (17%)	Dynamic (83%)
Usage of a Process Model	Yes (41%)	No (59%)
Model Scope	Single Entity (32%)	System (68%)
Verification and Validation	Conducted (62%)	Not Conducted (38%)
Time Horizon	Terminating (63%)	Non-Terminating (20%)

5.2 Examination of Digital Twins for their Characteristics and Dimensions

The analysis of the first 35 publications from the first iteration verified the dimensions and their characteristics in the taxonomy. The examined Digital Twins showed typical characteristics of a simulative application. Therefore, there were no blank dimensions and characteristics in the taxonomy. Just about 20 % of the examined publications did not describe the characteristic distinction of the respective dimension. From the 35 Digital Twins, nearly 60 % described a discrete progress in time, while 20 % described a continuous time progress. More than two thirds of all investigated Digital Twins are stochastical. The remaining third describing deterministic Digital Twins are mostly considering analytical procedures like the finite element method, which is used for structural analyses (e.g., in Moussa et al. 2018). 80 % of the Digital Twins contain a dynamical model, while the remaining 20 % contain a static model. The question, whether a process model was used was difficult to address. Just 40 % described the usage of a process model of any kind. Unfortunately, 60 % did not use or did not specify the usage of a process model, of which the usage would be beneficial, as mentioned in Section 2. The model scope was similarly less easy to classify. 34 % considered a single entity. The remaining 57 % considered a system of any kind as the foundation for their Digital Twin. Another important factor was the conduction of a verification and validation. More than two thirds of the examined publications conducted a verification and validation, while 31 % did not report such activities. The last dimension is the considered time horizon. 60 % of the Digital Twins considered a terminating system, while 20 % considered a non-terminating time horizon. Unfortunately, 20 % did not describe any time horizon at all.

The second iteration confirmed the observations from the first one. In the dimensions ”progress in time”, ”probabilities”, ”model character”, ”model scope”, and ”time horizon”, the distribution has become more unambiguous (see Table 1). In the two dimensions ”usage of a process model” and ”verification and validation conduction”, the distribution became more balanced. However, the strongest characteristic stayed the same. After all iterations, a Digital Twin for simulative applications is mostly described as follows: The Digital Twin describes a discrete system (67%) with stochastic (72 %) inputs. The model is dynamic (83 %), and no process model was used during the implementation of the model (59 %). The Digital Twins portrait mostly systems and networks (68 %). However, single entities are important as well, considering one third of all Digital Twins picture a single entity. In addition, most Digital Twins went through a verification and validation process (62 %) and contain a system with a terminating time horizon (63 %).

In this context, a Digital Twin has great references to the well-known discrete event simulation. If we consider an often-used definition of discrete event simulation given by Banks (2013), a discrete event simulation considers a discrete, probabilistic, and dynamic system, which is build with the usage of a process model and is both evaluated and verified. Therefore, we can assume that many Digital Twins in simulative applications are built in analogy to the already known discrete event simulation.

However, the given definitions of a Digital Twin (see Definitions 2 to 4) can not be matched with our taxonomy. The first property that a Digital Twin contains a physical and a digital part still applies very often. A simulation model forms the digital part, whereas the portrayed system forms the physical one. Yet, Digital Twins often neglect the data connection between the simulation model and the portrayed system. Hence, a Digital Twin shows great differences to a classical discrete event simulation, especially while considering the distribution of Digital Twin models as a Shared Digital Twin. A Shared Digital Twin is the concept of a Digital Twin that shares its data within a system or network (Cappiello et al. 2020). In this context, we have to stress the importance of data traceability and sovereignty while sharing data models (Otto and Jarke 2019). Hence, a Digital Twin must contain data usage policies that define access and sovereignty aspects for the shared usage of Digital Twins. An overview of eleven dimensions of a Digital Twin can be found in van der Valk et al. (2020). Part of these eleven dimensions are the data linkage between the digital and physical part, the Digital Twins purpose, the model accuracy, the data input and arguably most important, the synchronization between the physical and the digital part (van der Valk et al. 2020). The mentioned dimensions show the connection and differences between Digital Twins and simulation. Whereas simulation models can also be connected with the real system, this connection is one-directional, i.e., there can be a data flow from the system towards the simulation model. However, we see an automated data flow in the other direction, from the simulation back to the system, as very uncommon. The next dimension, the purpose, is the direct connection between Digital Twins and simulation, as the simulation is an application of the Digital Twin. We see the model accuracy and the data input equally important for simulation purposes and Digital Twins. Lastly, the synchronization between the system and the Digital Twin is a very important distinction between Digital Twins and simulation (Koulamas and Kalogeras 2018). During our research, we could confirm this distinction. Whereas most publications sorted into the continuous time progress characteristics mentioned a synchronization between the Digital Twin and the real world product, a synchronization was merely mentioned in the deterministic Digital Twins. Therefore, we have to determine that many shown usages of Digital Twins in the above-examined publications are not describing a proper Digital Twin but classical simulation processes.

6 CONCLUSION, LIMITATIONS, AND OUTLOOK

In this paper, we developed a taxonomy of Digital Twins in simulative applications. For this purpose, we analyzed well-known and often-used definitions of simulation and derive seven dimensions with fourteen characteristics. These characteristics describe the foundation of simulation studies. Simultaneously, we conducted a structured literature review on Digital Twins and simulation. Following the conceptual-to-empirical way, we selected 69 Digital Twins that describe an application in simulation studies for our taxonomy. We could derive a meaningful description of Digital Twins in simulative applications. With our taxonomy (see Table 1), we answer our first research objective (**RO1**). A typical Digital Twin in simulative applications pictures a discrete, stochastic, and dynamic system. It uses no process model for the implementation, but conducts a verification and validation and portraits a terminating system. The authors attribute the research results obtained in particular to the central application domain of digital twins, production, and manufacturing. The observations are consistent with the basic understanding that especially discrete event simulation models are used in this application context to study such complex systems. Although our understanding of the use of a procedure model was rather broader than described in Section 2, the result is surprising regarding its use in the application of simulation models in Digital Twins. Furthermore, this description shows significant similarities to the definition of the discrete event simulation and neglects important aspects of the definitions of Digital Twins. The publications do not describe a data connection between the digital and physical parts. Furthermore, the distribution aspects are not considered. Hence in accordance with our second research objective (**RO2**), the taxonomy shows a gap between the definitions of a Digital Twin and its most-used application, the simulation. Although simulation is the most important application of a Digital Twin, the concepts of simulation and Digital Twins are two different entities. Both can be connected to gain an efficient environment to analyze and optimize systems of any kind, but the concepts are not interchangeable.

Our research shows the typical *constraints* of literature reviews. The literature review is limited to the selected databases and might yield additional results when considering other databases. As we tried to restrict subjective influences to a minimum, we are convinced that we derived a profound base for our taxonomy. As *scientific contributions*, we see the opportunity that researchers can extent the empirical understanding of Digital Twins in simulative applications. In addition, it is possible to derive archetypical patterns for simulative Digital Twins. Furthermore, the gap between the concepts of simulation and Digital Twins provides vast opportunities to further research on the connection between both concepts. As *managerial contributions*, practitioners can determine properties for their respective Digital Twins under development with the purpose of usage in a simulative application. As taxonomies are extendable, more dimensions are addable during future researches. For example, additional dimensions that are less simulation-related like the synchronization aspect, could be added. Furthermore, the new dimensions can be grouped into meta-dimensions for further categorization.

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