Dimensions of Digital Twin Applications - A Literature Review

Completed Research

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Abstract

The use of Digital Twins has gained attraction in research and practice in recent years. Digital Twins are virtual representations of physical objects and they can be connected with their physical counterparts. Through this connection, Digital Twins contribute to the convergence of the real and the virtual world. While existing literature reviews focus strongly on the manufacturing industry, this paper analyzes Digital Twin applications across industries. Based on a systematic literature review, this paper examines 87 Digital Twin applications and proposes a classification scheme with six dimensions to describe the applications identified. The concept of Digital Twins is currently still underrepresented in Information Systems research, which opens up further research opportunities.

Keywords

Digital Twin, Literature Review

Introduction

The Digital Twin concept has gained increasing attention and popularity in both practice and research. The number of scientific publications on Digital Twins as well as their applications in practice have grown significantly within the last three years. Based on these numerous new findings, this paper provides an up-to-date overview of Digital Twin applications and presents a classification scheme for researchers and practitioners to enable them to better understand, describe, and develop Digital Twin applications. Gartner lists Digital Twins as one of the "Top 10 Strategic Technology Trends" for 2017, 2018, and 2019 (Panetta 2016, 2017, 2018) and Market Research Future predicts that the Digital Twin market will reach 35 billion USD by 2025 ("Digital Twin Market Size" 2019). In short, Digital Twins are virtual representations of physical products. There can be a connection between the product and its twin (Grieves and Vickers 2017). This connection allows to mirror the current state of the physical product to its digital counterpart (Hu et al. 2018). Based on the current and historical data of the Digital Twin, it is possible, for example, to predict future behavior (Sivalingam et al. 2018), run simulations (Ayani et al. 2018), and control the product (Dröder et al. 2018). This creates opportunities for business models (Klostermeier et al. 2018), services (Tao and Zhang 2017) and smart products (Abramovici et al. 2017).

Scientists contribute to research with conceptual approaches such as frameworks for the implementation of Digital Twins (Söderberg et al. 2018; Tao, Cheng, et al. 2018; Zheng et al. 2018; Zhuang et al. 2018) as well as with research on Digital Twin use cases (Dröder et al. 2018; Kurniadi et al. 2018; Sivalingam et al. 2018). Currently, there is little cumulative research in the Digital Twin literature. Furthermore, the existing literature reviews have a strong focus on the manufacturing or aircraft industry. The aim of this paper is to provide a cross-industry overview of current Digital Twin applications. Based on a structured review of scientific literature this paper aims to answer the following research questions: (1) In which industries are Digital Twins used? (2) What are the relevant dimensions of a classification scheme to describe application cases of Digital Twins?

Theoretical Background

The twin concept has been known at least since the 1960s. Twins were used for the first time in NASA's Apollo program. NASA built two identical space vehicles: the vehicle that remained on earth was called the twin. The twin can be described as a prototype, which replicates the real operation conditions to simulate behavior in real time. Before the mission started, the twin was used for training purposes. During the flight, the aim was to mirror the flight conditions of the space vehicle to its twin as precise as possible. The twin was then used to simulate different scenarios on earth to support astronauts in making decisions in critical situations. In the approach that was used during NASA's Apollo program the twin was implemented in hardware not in a digital form (Rosen et al. 2015). Michael Grieves (2014) introduced his concept of "virtual, digital equivalent to a physical product" or "Digital Twin" in 2003 in an Executive Course on Product Lifecycle Management at the University of Michigan. The proposed Digital Twin concept model consists of three main parts: the physical product, the virtual product and the connection between the physical and the virtual product. The digital part does not only carry historical data about the physical object but also delivers optimization and predictions. Tao et al. (2018) state that a complete Digital Twin should include five parts. They extended the three parts introduced by Grieves by the parts 'data' and 'service' and emphasize that every part of a Digital Twin is equally important. Table 1 provides an overview of the basic understanding of Digital Twins in scientific literature.

Authors	Definition
Tao et al. (2018, p. 2)	"[...A] complete DT [Digital Twin] should include five parts: physical part, virtual part, connection, data, and service."
Autiosalo (2018, p. 243)	"Digital Twin is the cyber part of a Cyber-Physical System."
Demkovich et al. (2018, p. 295)	"A Digital Twin of a production system is a multi-level digital layout that describes the product, processes and resources in the environment of their functioning, i.e. allowing to simulate the processes taking place in the real system, as well as collecting and displaying in real time data on the status of objects obtained from the PLC and sensors installed in the production system both on industrial equipment and in its environment."
Kritzinger et al. (2018, p. 1017)	"Based on the given definitions of a Digital Twin in any context, one might identify a common understanding of Digital Twins, as digital counterparts of physical objects."
Zheng et al. (2018, p. 2)	"In a broad sense, DT [Digital Twin] is an integrated system that can simulate, monitor, calculate, regulate, and control the system status and process."
Grieves and Vickers (2017, p. 94)	"Digital Twin (DT)—the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin."
Negri et al. (2017, p. 946)	"The DT [Digital Twin] 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."
Boschert and Rosen (2016, p. 59)	"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."
Grieves (2014, p. 1)	"The Digital Twin concept model [...] 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."

Glaessgen and Stargel (2012, p. 7)	"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 and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc.[sic]"

Table 1. Definitions of the notion of Digital Twins

The smallest common denominator of the definitions in Table 1 is that a Digital Twin is a virtual representation of a physical product. Some definitions emphasize the connection between the two parts whereas others include possible applications of Digital Twins such as simulation.

Research Aim and Research Design

The aim of this literature review is to give a comprehensive overview of the research on the application of Digital Twins across industries. Moreover, it aims to provide a classification scheme, which allows structuring the existing applications. The following paragraphs describe how the relevant literature was identified and analyzed. The procedure bases on the methodology proposed by Webster and Watson (2002) for writing structured literature reviews in the Information Systems (IS) discipline. The literature review follows a three-step process: (1) the development of criteria for the selection of relevant publications, (2) a literature search approach, and (3) an analysis scheme for the identified publications.

First, the selection of the relevant literature bases on form and content. With regard to the formal criteria, publications have to be published in a journal or a conference proceeding, as book chapters or reports. Extended abstracts, research ideas and magazine articles were not selected. The content-related criterion for the selection of publications was that the paper contains the concept of Digital Twins as a central element. Publications, which mention Digital Twins only in the abstract, introduction, or conclusion, were excluded. Second, the following databases were used for the structured search (in alphabetical order): ACM Digital Library, AIS eLibrary, IEEE Xplore Digital Library, Science Direct, and Springer Link. Additionally, a search in the Web of Science was performed. The search was carried out in November 2018 and limited to results from the years 2000 to 2018. The search terms used were based on the key concepts and their synonyms from the conceptualization proposed by Holler et al. (2016): "digital twin", "product avatar", "product agent", "product shadow", "information mirroring model", and "cyber-physical equivalence". They were applied in singular and plural forms within the title, abstract, and, if available keywords. The relevant papers were then identified based on the criteria described above. Within the selected papers, we conducted a backward search to determine additional relevant articles. Third, the relevant papers were first classified as conceptual or as application of Digital Twins. Papers were classified as 'conceptual' when they deal with the construct Digital Twin in a more theoretical way like developing frameworks and looking at Digital Twins from different conceptual perspectives. Papers were classified as 'application of Digital Twins' when the concept of Digital Twins is applied to address problems in a specific domain (e.g. in manufacturing) or to evaluate conceptual research (e.g. application of a framework).

Results

In total, the initial search resulted in 213 papers, which mentioned at least one of the search terms. The backward search resulted in 15 additional papers. The additional search in the Web of Science delivered no additional results. After applying the selection criteria to all papers, we identified 152 relevant papers in total. The number of published papers has increased strongly in the last three years. In the years from 2002 to 2015, 18 papers, in the last three years (2016 - November 2018) 134 papers were published (Figure 1 left). The following publication types were found (ordered by count in parenthesis): Journal Articles (82), Conference Proceedings (60), Book Chapters (9) and Report (1) (Figure 1 right).

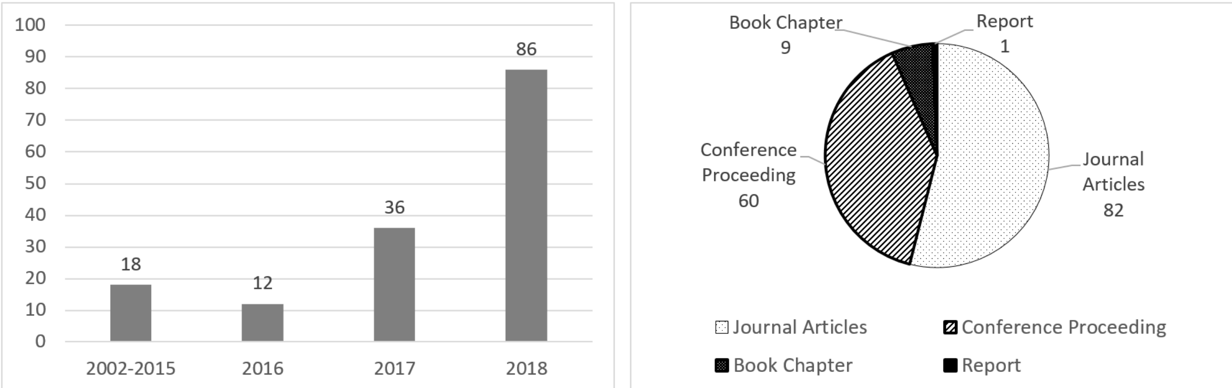

Figure 1. Number of relevant publications regarding time (left) and publication format (right); the results consider publications until November 2018

Digital Twin Literature Reviews

Within the relevant literature, five literature reviews on the topic of Digital Twins have been identified. Four literature reviews discuss Digital Twins in the context of the manufacturing industry, one in the context of aircraft industry (Table 2). The two latest literature reviews consider literature until August 2018 (Tao, Zhang, et al. 2018) and December 2017 (Kritzinger et al. 2018). Two literature reviews focus on the application of Digital Twins, one on concepts of Digital Twins, one provides an overview of definitions of Digital Twins, and one discusses Digital Twins from an aerospace perspective. In contrast to the existing literature reviews, which focus on a particular industry, this paper considers multiple industries and focuses on the development of a classification scheme for Digital Twin applications.

Authors	Number of papers considered	Focus
Tao, Zhang et al. (2018)	50	Application of Digital Twins in the manufacturing industry.
Kritzinger et al. (2018)	43	Areas of application in the manufacturing industry.
Negri et al. (2017)	26	Definition of Digital Twin and its role in Industry 4.0.
Holler (2016)	38	Concepts and current state of research of Digital Twins in manufacturing industry.
José et al. (2015)	n/a	Implications of Digital Twins in aircraft industry.

Table 2. Digital twin literature reviews

Paper Classification

In the classification process, 77 papers were classified as conceptual papers and 87 papers as Digital Twin applications. 24 papers include a conceptual and an application part and were therefore classified into both categories. For the following dimensions of Digital Twin applications, we focused on the application specific papers.

Dimensions of Digital Twin Applications

For the analysis of Digital Twin applications, we followed the concept centric approach proposed from Webster and Watson (2002). As the result of the conceptualization of the 87 application based papers, the following six dimensions have been identified: industrial sector, purpose, physical reference object, completeness, creation time, and connection.

Industrial Sectors Referenced in Digital Twin Applications

It was observed that Digital Twins are used in different industrial sectors. The identified industrial sectors where Digital Twins are applied are (ordered by count in parenthesis): manufacturing (54), aerospace (5), energy (4), automotive (3), marine (3), petroleum (2), agricultural (2), healthcare (2), public sector (1), and mining (1). Ten of the application specific papers could not be assigned to a specific industry because they deal with cross-sectional topics such as augmented reality. Two thirds of Digital Twin applications reside in manufacturing, one-third in all other nine industries.

Purpose of Digital Twin Applications

The purpose dimension describes three different types of Digital Twin applications. The applications of Digital Twins have been divided in the following three purposes (ordered by count in parenthesis): simulation (47), monitoring (32) and control (23). A specific Digital Twin application can be assigned to multiple purposes. The simulation purpose contains applications, where the behavior of physical objects can be reproduced in a virtual space. This allows planning or optimizing products or production plants without having to rely on the physical object. The monitoring purpose includes all applications focusing on the representation of the current state and its interpretation of a physical object. The control purpose covers applications, where Digital Twins directly influence products or manufacturing assets.

Physical Reference Objects of Digital Twins

The third dimension describes the physical reference object (Physical Twin) which is the physical counterpart of a Digital Twin. According to the definitions of Grieves (2014) and Tao et al. (2018) one main part of Digital Twins is the physical part. The following four categories of physical objects have been identified (ordered by count in parenthesis): manufacturing asset (45), product (27), human (2), and infrastructure (2). Eleven papers could not be assigned to a specific physical reference object because they are concerned with cross-sectional topics like augmented reality. Manufacturing assets are all machines and systems, which are used within a production plant. Manufacturing assets are staying in the same production line for the most of their lifespan. The term manufacturing asset covers physical objects from a single cutting tool of a CNC milling machine (Botkina et al. 2018) over robotic wok cells (Priggemeyer et al. 2018) up to complete production lines (Vachálek et al. 2017). Products refer to physical products created by manufacturers to address the needs of their customers. In contrast to manufacturing assets, products will leave the area of influence of the producer at a certain point in their lifecycle. For example, Schleich et al. (2018) proposes the use of Digital Twins of products during the production phase for geometry assurance. Sivalingam et al. (2018) use a Digital Twin to predict the remaining useful life of a product (wind turbine power converter). Further physical reference objects are infrastructures in terms of cities, streets or tracks. Mohammadi and Taylor (2017) present a smart city Digital Twin paradigm in which they build a Digital Twin of an entire city. Lieberman et al. (2017) apply the Digital Twin idea to an urban underground infrastructure. The authors of both papers intend to optimize operations, reduce construction costs, or create new smart city services. Graessler and Poehler (2017, 2018) use the idea of Digital Twins to represent humans (employees) within a production system.

Completeness of Digital Twins

The dimension of completeness can be measured by the number of represented features of the physical object by the Digital Twin like for example geometry, temperature, humidity, or power consumption. Grieves and Vickers (2017) state that an optimal Digital Twin can provide every information about a physical object which can be gathered from the physical object itself and therefore the Digital Twin can be considered to be complete. Within the relevant literature, 44 papers do not explicitly describe the number of represented features, but cover at least one. 13 papers name one to three features and 30 papers name four or more features explicitly. Due to these findings, the dimension completeness is divided into two categories (count in parenthesis): applications with one to three features (57) and applications with four or more features (30). For example Yan et al. (2018) present a Digital Twin which mirrors two features of a robot: torque and trajectory. Sivalingam et al. (2018) present a Digital Twin of an offshore wind turbine power converter which represents multiple features such as wind speed, ambient temperature, yaw angle, actuation cycles, and electrical power generated.

Creation Time of Digital Twins

The creation time describes whether a Digital Twin is created before or after its physical counterpart. Creation time can be divided into two categories (count in parenthesis): Digital Twins can be created before the Physical Twin exists (11) or at any later point during the existence of the Physical Twin (76). Grieves and Vickers (2017) state that when a Digital Twin is created before a corresponding Physical Twin exists, it is called a Digital Twin prototype. When the Digital Twin is bound to a physical object, it is called a Digital Twin instance. Alaei et al. (2018) use a Digital Twin prototype during the product design phase to be able to get feedback from their customers without the need for time-consuming and expensive prototyping. Luo et al. (2018) describe how a Digital Twin instance can be built for a single component of an already existing CNC milling machine to add additional functionality, which allows them to predict failures and to alert in time to avoid serious damage.

Connection between Digital and Physical Twin

The last identified dimension of Digital Twins is the connection between the Physical and the Digital Twin. According to the definitions of Grieves (2014) and Tao et al. (2018), the connection between the physical and virtual object is a mandatory part of a Digital Twin. However, in our research we identified three manifestations of connection (amount in parenthesis): no connection (23), one-directional connection (39) and bi-directional connection (25).

No connection refers to a digital representation of a physical object without a connection to it. This can occur, for example, during the development of new products when no physical object is produced but a virtual representation of the product already exists. A one-directional connection from the Physical to the Digital Twin can be used to reflect the current state of the Physical Twin in its digital counterpart. Based on the information from the physical object, the Digital Twin can be used to simulate and analyze the physical object's behavior (Demkovich et al. 2018). For example, Luo et al. (2018) use a Digital Twin with a one-directional connection to predict machine failures. The bi-directional connection is a direct connection in both directions between the Physical and the Digital Twin. For example Malik and Bilberg (2018) created a Digital Twin of a robot to control it in a human-robot collaboration workplace. The difference to the one-directional connection is that the Digital Twin is able to control the Physical Twin without human interaction. Tao and Zhang (2017) use the term two-way connection for this scenario.

Table 3 summarizes the six identified dimensions of our classification scheme and their respective characteristics.

Dimension	Characteristics (Number of occurrences in parenthesis)									
Industrial Sector	Manufacturing (54)	Aerospace (5)	Energy (4)	Automotive (3)	Marine (3)	Petroleum (2)	Agricultural (2)	Healthcare (2)	Public Sector (1)	Mining (1)
Purpose	Simulation (47)		Monitoring (32)			Control (23)				
Physical Reference Object	Manufacturing Asset (45)		Product (27)		Human (2)		Infrastructure (2)			
Completeness	1-3 Features (57)			>4 Features (30)						
Creation Time	Before Physical Twin creation (11)			After Physical Twin creation (76)						
Connection	No Connection (23)		One-directional (39)			Bi-directional (25)				

Table 3. Dimensions of Digital Twin applications

Discussion

Based on a systematic literature review, we aimed to analyze in which industry sectors Digital Twins are used (RQ1) and to propose dimensions of a classification scheme to describe application cases of Digital Twins (RQ2). Therefore we examined the existing literature and followed the concept centric approach proposed by Webster and Watson (2002).

The results of our literature review make some important contributions to the IS literature. First, our research identifies 10 industries, in which Digital Twins are used and propose six dimensions to categorize the different applications. In this context, our conceptualization provides a more nuanced perspective on the application scenarios of Digital Twins across industries. This is in line with Holler et al. (2016), who explicitly mention the industrial sector as a dimension. Other existing literature reviews focus strongly on the manufacturing sector (Kritzinger et al. 2018; Negri et al. 2017; Tao, Zhang, et al. 2018), which our literature review also identifies as the main field of application (approx. two thirds of the applications identified). A reason for this could be that many production machines and products in this sector already have sufficient prerequisites for the use of Digital Twins, such as the connection of production machines to industrial IT systems.

Second, our proposed classification scheme could be used in further research to describe and compare Digital Twin applications or to identify similar patterns. The dimensions industrial sector, purpose, creation time, and connection relate to perspectives of the existing literature. The purpose dimension can be related to the "Focused areas in manufacturing" of Kritzinger et al. (2018, p. 1018). The creation time dimension can be related to the product lifecycle perspectives of Holler et al. (2016), Negri et al. (2017) as well as Tao et al. (2018). The connection dimension can be related to the idea of the three subcategories of the "level of integration" by Kritzinger et al. (2018, p. 1017). Within our research, we identified two additional dimensions: physical reference object and completeness. The most frequently considered physical reference objects are manufacturing assets. However, further physical reference objects have been identified where the challenge is that they are portable (products) or geographically distributed (infrastructure) and are therefore not within the direct (physical) sphere of influence of the manufacturer. This influences the complexity of the connection between Physical and Digital Twin. With regard to the completeness dimension, it should be noted that, due to technical and economic restrictions, it is hardly possible today to store all data of the Physical Twin in the Digital Twin (Grieves and Vickers 2017).

Based on the results and discussion of this paper, we propose the following definition of Digital Twins: "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 contrast to the existing definitions (Table 1) this definition covers an additional aspect of completeness in the sense that a Digital Twin can provide more information about a physical object than the object itself such as predictions (Sivalingam et al. 2018) or simulation results (Ayani et al. 2018). The results delivered by a simulation may also be obtained directly from the physical object but with a Digital Twin, this information can be provided without the need of the physical object, which allows minimizing downtimes of production assets for example.

Proposition for Further Research

The concept of Digital Twins is currently not much discussed in IS research (the relevant literature identified in this paper includes only one paper from the AIS eLibrary). Shim et al. (2019, p. 133) emphasize in their "IS Research Agenda for IoT [Internet of Things]" that the difference between the Internet of Things and most other new information technologies is that a physical object connected to a virtual space exists. The connection of physical and virtual space is one of the core aspects of Digital Twins. Therefore, further studies on Digital Twins could contribute to the Internet of Things related research in the IS discipline.

Based on our findings, we propose three directions for further research: (1) Due to the many applications of Digital Twins in the manufacturing sector, these applications could be examined more closely in order to gain insights for the application of Digital Twins in other industries. (2) Within our literature search, we identified 77 conceptual papers. They include the examination of single aspects of Digital Twins as well as frameworks for their design and implementation. A next step could be to analyze the proposed frameworks for similarities and differences to gain deeper insights on how to develop and model Digital Twin applications. (3) The presented classification scheme in this paper can be used as a starting point for the development of a taxonomy according to the proposed methodology by Nickerson et al. (2013). In addition, it could be investigated which consequences arise from the use of Digital Twins in practice, e.g. with regard to opportunities, risks, cost-effectiveness or business models.

Limitations

The literature search process could be a limitation of this paper. Only the databases ACM Digital Library, AIS eLibrary, IEEE Xplore Digital Library, Science Direct, and Springer Link have been used for the search. Therefore, other relevant papers concerning Digital Twins could be missing. Despite careful selection, not all keywords may have been captured for the literature search. Within the literature review, the selection of relevant papers and the development of the dimensions might have been affected by subjective interpretations.

Conclusion

The key concept of Digital Twins is to connect the real and the virtual world. This paper proposes a conceptualization of Digital Twin applications across industries and enhances existing definitions for Digital Twins. This work is intended to help researchers and practitioners alike to get an overview of current Digital Twin applications in order to better understand and describe Digital Twins. The proposed dimensions industrial sector, purpose, physical reference object, completeness, creation time, and connection and their characteristics contribute to the description and understanding of Digital Twin applications. Especially for practitioners, this classification scheme can provide an initial basis for planning and developing new Digital Twin applications.

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