A Systematic Literature Review on Digital Twins

Seminar Paper

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Abstract

Digital Twins are gaining more and more attention and their development and state of research is changing rapidly in recent years. Digital twins are a virtual representation of a real physical system. A data communication line is used to communicate permanently and in real time, and the Digital Twin is constantly fed with real data, trying to monitor and optimise the real system. Digital twins offer several advantages and open up new possibilities for industry. This literature review defines Digital Twins and introduces their concepts, then describes their areas of application, shows how they can be implemented, addresses the important issue of data management and finally presents their benefits and challenges. Based on a systematic literature search, the literature review shows the current state of the art in academia and industry and the prospects for the future.

Keywords: Digital Twins, Applications of Digital Twins, Opportunities and Challenges of Digital Twins, Systematic Literature Review

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1 Introduction

A digital twin is a virtual, simulated representation of a real, physical product. It is an adaptive model that emulates a physical system in a virtual environment (Semeraro et al., 2021). The Digital Twin is connected to the real product via a data link, and complex physical models, sensor data of the real product and other information are used to create the most accurate possible representation of the physical product (Schleich et al., 2017; Tao et al., 2017). Using continuous real-time data, the Digital Twin can update its own behaviour during its life cycle. The (data) connection between the real product and the virtual, simulated representation and its information exchange is the most important factor here (Tao et al., 2017). The Digital Twin can suggest real-time actions to optimise and/or mitigate unexpected events by continuously monitoring and evaluating the operating profile. This innovative technology enables efficient and preventive management of physical systems by simulating and monitoring virtual systems in real time. (Semeraro et al., 2021). The Digital Twin replicates the physical system to predict potential failures and changes (Semeraro et al., 2021).

Due to the enormous progress in digitisation as well as in related technologies (e.g., internet of things, big data, real-time sensors or data management) and the new possibilities that come along with it, the interest and thus the research and use of Digital Twins has increased enormously in the past years (Jones et al., 2020; VanDerHorn and Mahadevan, 2021). Not only in the industrial field, but also in academia, a lot of research, development, and solutions for implementations have been done since then (Jones et al., 2020). This is especially visible by the massive increase in literature publications, methodologies, concepts and implementations of Digital Twins (Jones et al., 2020; VanDerHorn and Mahadevan, 2021). The first concept of Digital Twins goes back to Michael W. Grieves (2014). Back in 2003, he introduced a first, rough version of a Digital Twin in a presentation (Lim et al., 2019). In his white paper from 2014, he then introduced and explained the full concept of a Digital Twin (Grieves, 2014). After Grieves introduced and popularised the concept in 2014, the Digital Twin technology even made it to number four in the "Gartner Top 10 Technology Trends" in 2019[1]. Due to the strongly growing interest in Digital Twins in the past years and the associated great progress through research and application of Digital Twins (VanDerHorn and Mahadevan, 2021), there are now some deviations from the original definition of Grieves (Jones et al., 2020). Furthermore, the definition and understanding of Digital Twins in general varies in the literature and there are no completely unified approaches, concepts as well as integrations into the business (Chabanet et al., 2023; Boyes and Watson, 2022; VanDerHorn and Mahadevan, 2021).

The technical approaches, analysis methods and challenges related to data collection and integration are the main focus of the current literature on the Digital Twin. However, there is a lack of practical implementation examples that consider how to implement and support decision making (VanDerHorn and Mahadevan, 2021). Technical and cultural challenges and the integration of a variety of enabling technologies must also be considered in a successful implementation strategy (VanDerHorn and Mahadevan, 2021). Accordingly, the goal of this paper is to provide an overview of the current state of research and industry as well as the current concept, applications and implementation strategies of Digital Twins.
This literature review illustrates the conceptual design of Digital Twins and refers to the currently available literature. Through systematic literature research, application areas, implementation strategies/requirements, data management and the benefits as well as challenges will be discussed. Thereby, existing gaps in research and literature will be identified and recommendations for the future will be provided. The goal here is to comprehensively demonstrate the full potential of Digital Twins. The research questions are what the state of the art of literature on Digital Twins is and how Digital Twins can be used effectively in industry to optimise production processes and reduce costs, and what needs to be considered.

[1] Gartner Top 10 Strategic Technology Trends for 2019, Gartner (https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019)

2 Method

In order to provide a high, substantive quality of the literature review, the systematic literature search was applied, which divides the identification of the relevant literature into three different steps: Literature Search, Literature Selection and Qualitative Analysis.

Literature Search

I applied the concept of Webster and Watson (2002) to search out initial literature. Through this systematic way of searching and finding literature, I was able to identify a great amount of relevant literature on the topic of Digital Twins.
In a Preliminary Search, for a rough overview of the topic, I searched for literature via Google Scholar. I used general search terms such as "Digital Twins" or "Digital" AND "Twins" to get an initial overview. I then searched for keywords such as "Applications", "Technologies", or "Implementations" related to "Digital Twins".
After that, I searched much more specifically. In databases such as EBSCO, IEEE Xplore, Springer Professional, or Science Direct, I searched for peer-reviewed papers that included the search terms in the title ("TI TITLE") and/or abstract and which were written in English. Terms like "Digital Twins", "Digital Twins" AND "Application", "Digital Twins" AND "Implementation" then led me to highly relevant literature. This search then resulted in a literature list of 182 papers, which I built up in a structured way. Search strings and settings, title, DOI, ISSN, VHB ranking, number of citations for example are stored in the list. Via "ConnectedPapers" I additionally searched and found literature that have a close content connection to my already included papers.

Literature Selection

In order to identify a manageable number and only the most valuable papers in terms of content, I have filtered and sorted out the literature based on various criteria. The first step was to mark and then remove duplicates that arose during the search. I then read through the titles of all the papers and threw out those whose main content did not fit to Digital Twins. When these papers were removed, I read the abstracts of the remaining papers. Again, I removed the literature whose main content was not related to Digital Twins. I made a few exceptions if, for example, it was a great application example for Digital Twins. The last two criteria are the ranking (VHB) and the number of citations of the papers. I limited myself here to the best rankings available (B and C) - but here I made a few exceptions if the papers had very often been cited, too. In the end, 24 papers remained to be used for the literature review.

Qualitative Analysis

In order to now evaluate the literature intensively and to complete the systematic analysis of the now available literature, the qulitative analysis according to Wolfswinkel et al. (2013) was used. Here, the focus lies on three steps: Open Coding, Axial Coding and Selective Coding.
In the first step, the Open Coding, I identified and broke out key concepts, categories, or specific themes from the literature. Next, within the Axial Coding, I categorised the excerpts and thus merged similar topics or categories. Last, during the Selective Coding, these categorisations were now merged and related. This allowed these information to be brought together into a larger context.

3 Results

Category / Papers	Definition/ Concepts	Appli-cation	Implemen-tation	Data Ma-nagement	Benefits/ Challenges
Agnusdei et al. (2021)	•	•			
Boyes and Watson (2022)	•	•			•
Chabanet et al. (2023)		•			•
Cimino et al. (2019)	•	•	•	•	
Greif et al. (2020)	•	•			•
Grieves and Vickers (2016)	•	•		•	•
Jones et al. (2020)	•				
Korotkova (2023)		•		•	•
Lim et al. (2019)	•				
Liu et al. (2019)	•	•	•		
Negri et al. (2017)	•	•		•	
Perno et al. (2022)	•	•	•		•
Psarommatis and May (2022a)	•			•	
Psarommatis and May (2022b)	•		•		
Reim et al. (2023)	•			•	•
Saracco (2019)	•	•			•
Semeraro et al. (2021)	•	•	•		
Schleich et al. (2017)	•	•			
Tao et al. (2017)	•	•		•	•
Tuegel et al. (2011)	•	•			•
VanDerHorn (2021)	•	•	•		•
van der Valk et al. (2022)	•	•		•	
Vieira et al. (2022)	•				
Zeb et al. (2022)	•	•		•	•

Table 1. Concept Matrix

3.1 Definitions and Concepts

The first person to talk about or introduce Digital Twins was Grieves (2014) in his white paper (Grieves, 2014). At a lecture in 2003, he set up a very first, rough form of a Digital Twin, which coupled a physical, real system to a virtual model for the first time (Lim et al., 2019). Originally intended for NASA rockets, Digital Twinss are now found in many more business sectors and continue to gain popularity (Lim et al., 2019).

The definitions and concepts in the literature differ widely in some cases. There is no standard, uniform definition (Chabanet et al., 2023; Boyes and Watson, 2022; Cimino et al., 2019). Due to the rapid development of technology in recent years and the associated progress in Digital Twins (VanDerHorn and Mahadevan, 2021), they have developed into quite different use cases and are implemented using different concepts.

In order to show these differences in the definition from the literature, some frequently cited papers have been used in the following table to show their definition of Digital Twins over time.

Authors	Year	Citations	Definition
Tuegel et al.	2011	606	"[The Digital Twin is a] reengineering of structural life ultrahigh fidelity model of individual aircraft by tail number [...] to integrate computation of structural deflections and temperatures in response to flight conditions, with resulting local damage and material state evolution. [...] The Digital Twin is a reengineering of structural life prediction and management."
Glaessgen and Stargel	2012	1969	"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."
Grieves and Vickers	2016	701	"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."
VanDerHorn and Mahadevan	2021	209	“A virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems.”

Table 2. Best known and most frequently used definitions of Digital Twins over time

The characteristics or concepts of Digital Twins are rather similar in the literature compared to the definitions. As VanDerHorn and Mahadevan (2021) write, Digital Twins are basically classifiable into three characteristics: (1) Physical reality, (2) Virtual representation and (3) Linking of (1) and (2) to exchange information (VanDerHorn and Mahadevan, 2021).
The physical reality (1) is the object to be modelled, i.e. the system under consideration and its environment and processes (VanDerHorn and Mahadevan, 2021).
The virtual representation (2) is the actual Digital Twin, the definition of which, as already shown in Table 2, varies a lot. The aim is to represent the physical component as accurately as possible in this virtual representation, the Digital Twin (VanDerHorn and Mahadevan, 2021). Characteristics, parameters, variables, dimensions, etc. are used. (VanDerHorn and Mahadevan, 2021), the real system should be simulated as perfectly as possible. In this way, the environment of the physical component is also simulated and integrated as realistically as possible (VanDerHorn and Mahadevan, 2021).
The connection between (1) and (2), the interconnection (3), represents the communication link through which the real system can and should communicate with its Digital Twins and exchange data. Here it goes in both directions: From the real system to the Digital Twin as well as from the Digital Twin to the real system. There is also information fusion, where data from both systems are combined, eliminating duplication and redundancy (VanDerHorn and Mahadevan, 2021).

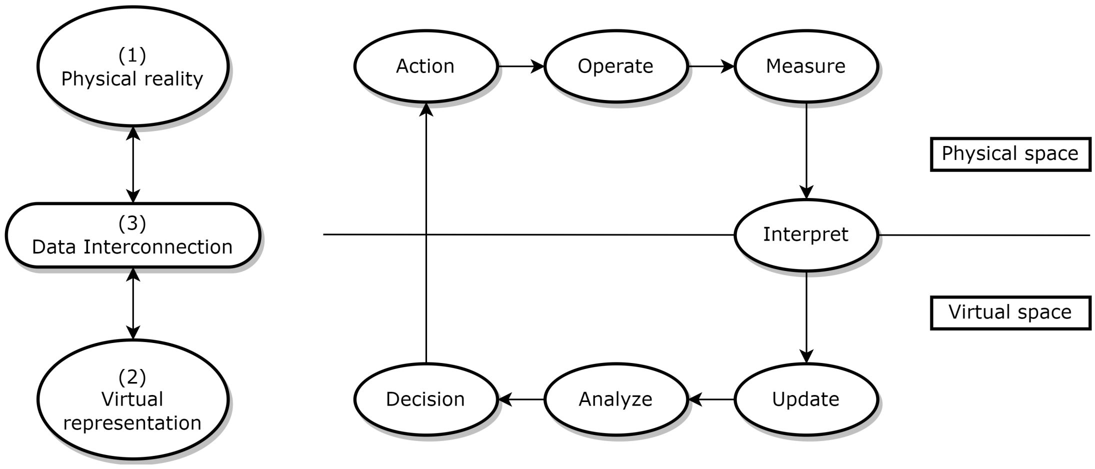

Figure 1. Own representation on the concept of a Digital Twin based on VanDerHorn and Mahadevan (2021)

Tao et al. (2017) also summarised the characteristics or concept of Digital Twins into three points: real-time reflection, interaction/convergence and self-evolution. Real-time reflection states that there are two spaces, the real space with the physical system, and the virtual space with the Digital Twins (Schleich et al., 2017; Chabanet et al., 2023). The Digital Twin is the simulated reflection of the physical world with ultra-high synchronisation and fidelity. Interaction and convergence is divided into three different sub-items. (a) describes the interaction and convergence in the physical space, where the data, phases and processes within the physical world are merged. (b) is the interaction and convergence between historical and real-time data that creates a deep understanding. (c) then describes the interaction and convergence between the physical and virtual space. These are not separated individually, they are brought closely together. Finally, the self-evolution. The Digital Twin can evaluate and change data in real time, so that the virtual model is constantly evolving (Tao et al., 2017).

Zeb et al (2022) has divided Digital Twins into three variants. The first categorisation criterion is the ability of a Digital Twin to describe the past and present state of the physical twin ("descriptive Digital Twin"); the second to predict the state, function, behavior, and dynamics of the physical twin ("predictive Digital Twin"); and the third to enable driving the physical twin to or towards a desired future state ("prescriptive Digital Twin"). In general, a descriptive Digital Twin would be based on the data gathered from the physical twin and the environment and on representing it in an informative way. This may include data analytics and other means of processing the data from the sensors and other sources into an intuitive form. A predictive Digital Twin would require the capabilities to estimate the future trajectories of the physical twin's function and behavior based on the current information of the system and already collected historical data. Such a Digital Twin could be composed of physicsbased models (a priori knowledge of the behavior and dynamics of the target) or it could be purely based on the knowledge of behavior history and its data-predictive model (e.g., based on an artificial neural network model of the physical twin). A prescriptive Digital Twin would extend the predictive Digital Twin with optimisation or some other means of defining the controls and parameters of the physical twin in such a way that the physical twin will reach the desired state in a given time or get as close to it as possible. In the last two types of Digital Twins, the fundamental element of the Digital Twins is the ability to predict the future state and behavior of the physical twin. This is inherently to do with physics-based simulation (Zeb et al., 2022).

3.2 Applications

Since the idea and introduction of the concept of Digital Twins, it has been implemented and applied in many different areas (Psarommatis and May, 2022a; Reim et al., 2023). The great potential is already clearly visible in several industrial sectors (Tao et al., 2017).
The previously mentioned definitions, concepts and characterisations are not of great relevance for the final application or the field of application of a Digital Twin. They are important for the communication, presentation and conception of Digital Twins, but not for the final field of application. While the definitions allow clearer communication about all the necessary capabilities and implementations, the real added value for the concepts and designing of Digital Twins comes from its application areas, not from the theoretical definitions (Zeb et al., 2022).

When considering Digital Twins, Negri et al. (2017) categorised Digital Twins into three complexities for application. (1) Lightweight digital twins have a relatively simple structure, which enables high-performance and fast processing (Boschert and Rosen, 2016; Grieves, 2014; Kunath and Winkler, 2018). (2) Multi-physics, multiscale simulation systems can merge different models, data and also information for the first time (Shafto et al., 2012). (3) Autonomous systems enable more in-depth functions, such as automating decision-making without reconfiguration, even for unexpected situations (Rosen et al., 2015).
For these three levels of complexity of a Digital Twin, Klostermeier et al. (2019) defined three different application fields of Digital Twins. (1) Simulation in development, (2) Operation of products and systems and (3), Product Life-Cycle Management (Klostermeier et al., 2019; Cimino et al., 2019).
Grieves (2014) additionally describes in his paper, in which he defines Digital Twins fully for the first time, that the use case of Digital Twins includes and supports three of the most important and powerful tools of human knowledge. These are conceptualisation, comparison and collaboration (Grieves, 2014):
Conceptualisation means that People evaluate situations, they understand the problem and its context, and they gather the information. However, the current process of converting visual data into symbols and back again is wasting time and causing valuable information to be missed. To be efficient, we need to eliminate these ineffective steps, and this is where Digital Twins come in. (Grieves, 2014).
The idea of comparison is the next tool that humans use to evaluate situations. We compare unknowingly and continuously our intended result with our current result in order to detect a difference. Then we choose how to resolve this discrepancy (Grieves, 2014).
One of the most powerful capacities of human beings is cooperation. Cooperation leads to the combination of intelligence, variability of perspectives and more effective problem solving and innovation. However, this is where the dependency of individuals exists. Digital Twins can solve the problems with unlimited number of people, irrespective of location, etc. (Grieves, 2014).

Digital Twins are used for different tasks in different industries (Psarommatis and May, 2022a; Greif et al., 2020). In manufacturing, Digital Twins are mainly used to collect product lifecycle data for predictive maintenance (Tao et al., 2017; Vachálek et al., 2017). They can monitor and analyse systems in real time and even intervene and thus optimise them (Tao et al., 2017).
In the aerospace industry, individual components and even entire systems are being developed as Digital Twins for monitoring and predictive maintenance (Glaessgen and Stargel, 2012; Tuegel et al., 2011; Cimino et al., 2019). The US Air Force Research Laboratory, for example, has developed a Digital Twin that represents a highly complex flight model and links the virtual with the real space/model (Tao et al., 2017). This makes it much easier to predict when and where breakdowns and component failures may occur (predictive maintenance) (Tuegel et al., 2011).
In the healthcare industry, Digital Twins are being used to connect portable medical devices to Digital Twins so that they can be monitored continuously and the information can be used to make appropriate diagnoses (Liu et al., 2019; Greif et al., 2020). The healthcare sector is one of the most promising

industries. It is assumed that within the next decade there will be opportunities to develop a Digital Twin for every human being. This will make it possible to monitor the state of health on an ongoing basis (Saracco, 2019).

However, there are also industries in which Digital Twins are currently still being used very rarely (van der Valk et al., 2022). One industry in which Digital Twins are currently still having a very difficult and challenging experience is the oil and gas industry (Korotkova et al., 2023). Despite great, known potential, implementation is not yet effective and efficient enough today. Scope and Focus, Lack of Standardisation, Cyber Security as well as Data Ownership and Sharing are challenges which lead to the problems implementing Digital Twins in the oil and gas industry today (Wanasinghe et al., 2019).
One application area where Digital Twins have not yet entered well enough is industrial safety (Agnusdei et al., 2021; Cimino et al., 2019). By linking real and virtual space, more reliable risk assessments can be developed, safety-critical circumstances can be identified and better safety systems can be established (Bouloiz et al., 2013; Villa et al., 2016; Liu et al., 2018; Ma et al., 2019; Moi et al., 2020; Chang et al., 2011).

3.3 Implementation

In order to implement Digital Twins in your own company, some requirements and preparations are necessary. Since Digital Twins need for example different technologies and data and since it is quite complex to develop and implement them, some considerations have to be taken into account.
According to VanDerHorn and Mahadevan (2021), four points are absolutely necessary in order to integrate a Digital Twin into a business: the specification of the exact, desired end result or outcome, the precise and comprehensive development of the solution (clear definition of the physical, real system as well as the exact levels of abstractions), the development and creation of the virtual model, and finally the establishment of the data links and connections necessary for the Digital Twins (VanDerHorn and Mahadevan, 2021).
Tao et al. (2017) has a similar approach, which partly overlaps in content with that of VanDerHorn and Mahadevan (2021) already outlined. Tao et al. (2017) defines five key technologies that need to be researched or addressed in order to integrate Digital Twin driven product design, manufacturing, and service: (1) Intelligent perception and connection, (2) Virtual modeling, running simulation and verification, (3) Digital twin data construction and management, (4) Digital twin-driven operation technology, and (5) Smart production and precision service.
VanDerHorn and Mahadevan (2021) developed three categories of implementations of Digital Twins at the current stage. (1) Digital Twin component solutions, (2) Commercial off-the-shelf solutions, and (3) Custom hybrid combinations (VanDerHorn and Mahadevan, 2021). Variant (1), the Digital Twin component solutions, is often offered and used. They are mostly distributed by companies that offer platform services or digital models and simulations (VanDerHorn and Mahadevan, 2021). Typically, this includes components from the distributor companies that offer personal development and involvement of the Digital Twins and still leave the customer a lot of flexibility in the exact implementation (VanDerHorn and Mahadevan, 2021). The next category is off-the-shelf Digital Twin solutions (2). Mostly these are offered by the original industrial companies from their exact business area. The last category is the custom hybrid approaches (3), where the company develops its own Digital Twin or creates the solution. This category is the most effective solution, as the Digital Twin is developed for the exact business case. Also, features can be added or removed later and the Digital Twin can be increasingly optimised for its use case (VanDerHorn and Mahadevan, 2021).
According to VanDerHorn and Mahadevan (2021), five things are essential for successful implementation of a Digital Twin. (1) Data that were previously independent of each other must now be linked. (2) Developing calculation models and fully optimising them. (3) Estimation of the uncertainty to eliminate errors, noise and other confounding effects. (4) Continuous improvement of the results and their presentation and

(5) regular optimisation of the infrastructure for data management (VanDerHorn and Mahadevan, 2021). Cimino et al. (2019) breaks down implementation features into three bullet points. First comes the "Scope" (1), where the level of detail of the system to be represented as Digital Twin is described. Depending on the application and the size of the system (small component or whole machine), this scope can be very different. Next is the "Data Acquisition" (2), where all the information for data acquisition and processing is taken up. The used protocols for data transfer, the data set are considered here. The last point is the "Simulation Features" (3), which are closely related to the type of system. Here it is mainly about the software used and the type of simulation model that is or was developed for the Digital Twin (VanDerHorn and Mahadevan, 2021).

3.4 Data Management

Data analytics and Big Data are becoming essential for companies to stay competitive and develop competitive advantages. Data is also extremely important for Digital Twins - they thrive on it. Digital Twins combine the real, physical world with the virtual world (Tao et al., 2017; Schleich et al., 2017; Chabanet et al., 2023; Vieira et al., 2022). They are developed by implementing the data from the real, physical product into the virtual world and simulating it (Psarommatis and May, 2022a). Thus, two different worlds are brought together - and accordingly also many, different data. A Digital Twin compares and contrasts data from the real world (product lifecycle activities), as well as from the virtual world (result of Big Data and data analyses or predictions) (Tao et al., 2017).

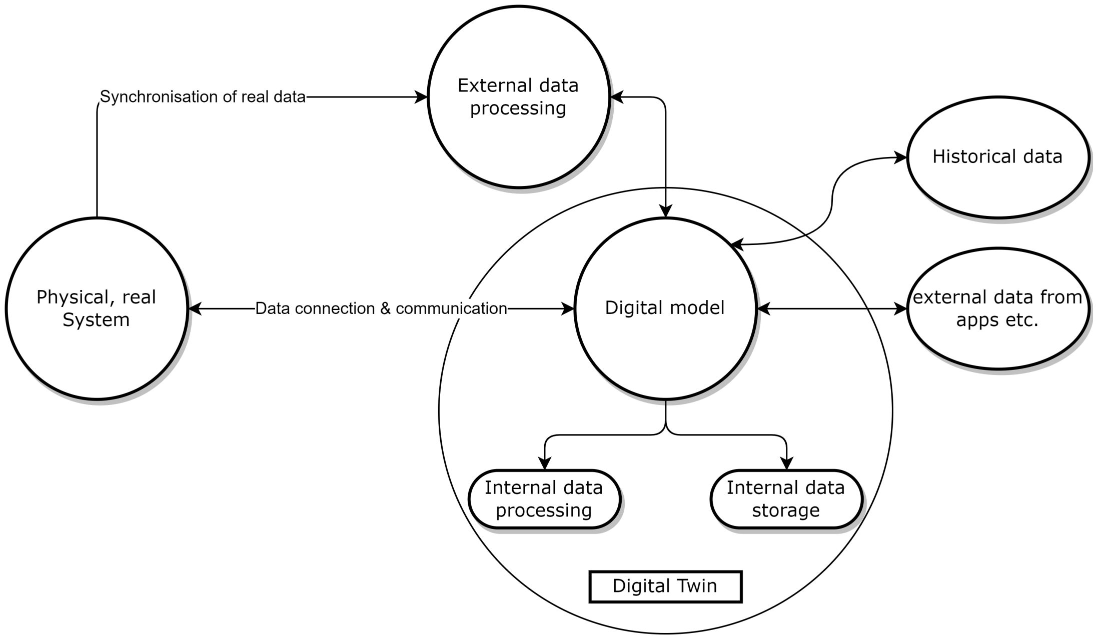

Figure 2. Own representation on the concept and data management of a Digital Twin based on van der Valk et al. (2022)

Van der Valk et al. (2022) have developed a taxonomy that describes the pass-through process of data in Digital Twins. There are three so-called meta dimensions: (1) Data Acquisition, (2) Data Usage and Distribution, and (3) Conceptual Scope (Van der Valk et al., 2022). Each of these meta-dimensions has multiple dimensions, such as for example: (1) data acquisition, data source etc., (2) data governance, data link etc., and (3) accuracy, time of creation etc. (Van der Valk et al., 2022).
Depending on the product for which a Digital Twin will be developed, different types and amounts of data are needed (Psarommatis and May, 2022a). For example, depending on the technology, it varies whether

live data and/or historical data are needed for the Digital Twin (Psarommatis and May, 2022a).
Likewise, the number of input parameters is crucial for the data of Digital Twins. If this number is fixed to a certain value, the way of Digital Twin can only be used for this one method or application and it is not flexible at all for other application areas (Psarommatis and May, 2022a).
Bringing the physical and virtual worlds together has huge benefits because using this data, the Digital Twin can extremely optimise and improve the entire product cycle of an object. Using this data, simulations can be created and viewed, the Digital Twin and its real product can be permanently monitored, and optimisations can be efficiently and effectively implemented (Tao et al., 2017). Also, the previously unnecessary and inefficient duplicates in the data can be discovered and removed by Digital Twins (Tao et al., 2017).
However, there are still some problems with the data management of Digital Twins. There are major uncertainties and ambiguities in the handling, transfer and confidentiality of data in cross-company collaboration (Reim et al., 2023). Data is essential for Digital Twins, but it is often unclear who owns the data and to what extent and what data is shared (Reim et al., 2023). Reim et al. (2023) summarised three overpoints where there are currently problems with the data management of Digital Twins working together: (1) lack of commitment to provide product- and process-specific data, (2) lack of commitment to provide code-specific data, and (3) insufficient agreement on the property of the data used for the Digital Twin (Reim et al., 2023).
But there are more than just the problems with data sharing and ownership - Zeb et al. (2022) draws attention to additional, three risks associated with Digital Twin life cycle management: (1) Dependability and servicing risks, (2) Risks associated with human skills, and (3) Risks associated with coordination (Zeb et al., 2022).
Zeb et al. (2022) therefore proposes the following strategies to advance data life cycle management: (1) model specification standardisation, (2) open specification of formats and open languages for modeling, (3) broadly supported application-specific software formats, (4) source code of software, and (5) maintenance of the initial IT infrastructure (Zeb et al., 2022).

3.5 Benefits and Challenges

Digital Twins bring several benefits as well as opportunities, but there are also some disadvantages and challenges open to be faced.
Digital Twins bring a number of advantages and chances that can significantly advance industries in the future. In the example of the aviation industry, Digital Twins enable much better management and monitoring of the aircraft and its many components during its product life (Tuegel et al., 2011). The key advantage here is the great gain in information and the significantly better overview of the aircraft for all engineers involved (Tuegel et al., 2011). The result is that aircraft maintenance and repair can be planned much better and implemented more efficiently (Tuegel et al., 2011).
Perno et al. (2022) defined so-called "enablers" that are needed to get the full potential out of Digital Twins. Accordingly, the extent to which the potential and all the possibilities of Digital Twins can be exploited more fully depends on these technologies and their developments in the future (Perno et al., 2022). These "enablers" include: Artificial intelligence, (industrial) internet of things, virtual/augmented reality, hardware, communication technologies, knowledge building, design processing and development of technologies (Perno et al., 2022). Specifically, artificial intelligence is one of the most important technologies for Digital Twins and thus one of the most important factors for the advancement of Digital Twins (Fuller et al., 2020).
Digital Twins enable the exploitation of various other technologies and digitalisation trends such as big data, optimisation in production, diagnostics and monitoring, and the creation and development of forecasts (Perno et al., 2022).
Significant opportunities arise from Digital Twins because many systems with different data can now be brought together and linked (VanDerHorn and Mahadevan, 2021). The result of this merging of previously

separately handled data leads to a significant increase in efficiency as well as speed of data exchange and extraction (VanDerHorn and Mahadevan, 2021).

On the other hand, however, there are some disadvantages and challenges that are currently holding back the potential of Digital Twins and could lead to problems in the future which will have to be dealt with.
Technological advances such as extremely fast synchronisation or transfer of data between virtual and real worlds, extremely high computing power for real-time analysis and monitoring, and deep understanding and learning of the methodologies and design of Digital Twins are essential elements needed to advance Digital Twins (Tao et al., 2017). So, all these aspects are challenges which need to be mastered in order to extract all the potentials and opportunities from Digital Twins.
To this regard, Perno et al. (2022) defined so-called "barriers", analogous to "enablers", which limit the use and potential of Digital Twins. These include: System integration issues, Security issues, Performance issues, Organisational issues, Data quality issues and Environmental issues (Perno et al., 2022). System integration issues and security issues in particular slow down the potential and use of Digital Twins, which is why these topics will definitely have to be addressed in the future (Perno et al., 2022).
Furthermore, regulatory barriers (human, local, national, and international) are a challenge for the future (Tao et al., 2017). Furthermore, ideological aspects as well as the costs for Digital Twins are a major barrier especially for small and medium-sized enterprises (Tao et al., 2017). In addition, there are currently still too few standards and documentation to implement Digital Twins in a good and simple way (Tao et al., 2017).
Reim et al. (2023) additionally address the issues surrounding collaboration challenges. Disadvantages due to possible dependencies, the current uncertainties related to data management, the very different requirements of customers as well as the associated difficulties in the development of Digital Twins, inadequate working methods and inappropriate payment models are major challenges for the future of Digital Twins (Reim et al., 2023).
As already described in this literature review, there are problems regarding data management in the product lifecycle of Digital Twins. The dependency and service risks, human skill risks and coordination related risks are the aspects here (Psarommatis and May, 2022a). The rapid development of technology and thus the rapid obsolescence within few decades can also cause problems in the future (example: Windows XP and 32-bit in 2000 is totally obsolete today) (Psarommatis and May, 2022b).
Also, a very different challenge will be to bring trust to a technology like Digital Twins that has been highly hyped in recent years (Korotkova et al., 2023).
VanDerHorn and Mahadevan (2021) also address the challenge of standardization of technology and everything around Digital Twins. Collaboration and working together, especially in the area of data management, is also extremely important (VanDerHorn and Mahadevan, 2021). Even if business goals and secrets are compromised, collaboration needs to be strengthened to move Digital Twins forward - ownership clearly needs to be defined and secured (VanDerHorn and Mahadevan, 2021).

4 Discussion

Digital Twins are a relatively new topic that is developing very dynamically and has gained a lot of popularity in recent years. The understanding of definitions and concepts varies widely, as do the areas of application. This is particularly evident in the rapidly increasing number of publications from academic and industrial research.
The discussion is divided into three sections. I begin with the relevance and possible usages of this paper. Then I will discuss the future research and its potential - and what recommendations I make for it. Finally, I will discuss the limitations of this paper, which are highly relevant for the consideration of my interpretation and discussion.

Relevance

The paper has a high relevance for research and practice because the most important information of the current state of academic and industrial research on Digital Twins is summarised in a comprehensible way. This is one of the very few literature reviews that generally examine Digital Twins with all its most important aspects. The literature review helps to get an informative and comprehensive overview of the topic and to be able to evaluate in a differentiated way whether the implementation of Digital Twins would be suitable, could be economically worthwhile and which benefits and challenges would be faced in the decision for Digital Twins. By identifying the current application areas, all relevant implementation aspects and the technological as well as organisational barriers of Digital Twins, it can be evaluated whether the use of Digital Twins for the own business can/should be considered.
Furthermore, the paper provides a basis for further research and development of Digital Twins. Due to the very dynamic development around Digital Twins and the lack of information or different approaches in many areas, the paper shows which aspects need to be considered and further advanced. Which enablers exist that can significantly optimise Digital Twins and which barriers have to be mastered - these questions are clarified with the help of this paper.

Future Research and Potentials

The paper provides a strong basis for further academic and industrial research. The literature on Digital Twins is still very limited at this stage, and literature reviews on Digital Twins in general are rare. In order to exploit the full and promising potential of Digital Twins, research needs to be strongly promoted. Due to the partially large differences in the literature, which have been addressed in this paper, a systematic and comprehensible overview of the topic is possible, which prepares a necessary standardisation and unification of the topic.
By clarifying the essential and required enablers (Perno et al., 2022) for Digital Twins optimisation (Lim et al., 2020; Perno et al., 2022), it is possible to dive deeper into these topics. It also opens up and enables completely new areas of application (Lim et al., 2020).
By identifying the barriers (Perno et al., 2022), it becomes clear where the focus and challenges for the further development of Digital Twins lie. Not only technological, but also organisational and especially cultural aspects play an extremely important role in the development of Digital Twins and need to be addressed intensively.
Further advances in the associated technologies will greatly assist the development of Digital Twins. The paper and its overview of the current state of research will help to identify these technologies and apply advances in them directly to Digital Twins.
One of the most important aspects is also the clarification of ownership rights and the cooperation between different independent companies regarding data management. A lot of potential is currently being wasted by protecting powerful and valuable data from being shared.

Limitations

There are limitations to this literature review that need to be taken into account. Firstly, the subject of Digital Twins is relatively young and has become much more popular in recent years, which means that there is comparatively little literature to date. Many of the academic papers are from the last one to three years, some even from the year in which this paper was written. As a result, some of the literature used does not have a very high ranking or, in some cases, no ranking at all (e.g. VHB ranking: all papers used are B or C, some are also unranked). As research on Digital Twins has gained a lot of momentum and is therefore very dynamic, a lot of different and also divergent information can be found - the consensus is often not fully clear.
Secondly, I have approached the subject of Digital Twins as generally as possible, in order to be able to

offer a very comprehensive characterisation of Digital Twins across as wide a spectrum as possible. Some subcategories, details and other less popular aspects have been left out.
Thirdly, I searched only for peer-reviewed scientific papers in academic journals or conference papers in English, in order to achieve the highest possible scientific quality. This excluded, for example, books in general or other literature in languages other than English. Since I limited myself to a few databases, all potential results from other databases are not included in the literature review.
Fourthly, I mainly searched with strings containing only Digital Twins. Similar search terms from the same field, such as 'predictive maintenance', one of the main applications, were not included in the literature search as this would have gone beyond the scope of this review.
Finally, there are some general limitations in the field of Digital Twins, resulting from the fact that it is currently under-researched. The areas of safety and security in the field of Digital Twins are still under-researched and hardly applied at present. The architectures and design of Digital Twins are also still very limited and can only be found to a limited extent in the literature. Data and information management is also a major barrier that has not yet been sufficiently addressed.

5 Conclusion

The overall aim of this paper was to analyse and provide a clear overview of the current state of academic and industrial research on Digital Twins. In order to achieve this goal, the literature on Digital Twins was closely examined and Digital Twins were characterised and described according to the five most important and most described topics: Definitions/Concepts, Applications, Implementation, Data Management, Benefits/Challenges.
The first step was to show the current state of definitions and concepts in the literature, which is very different and has in some cases undergone significant changes over the last few years. This makes it possible to identify exactly where Digital Twins are applied and where it is not. It was then looked at the current areas of use and the areas where there is currently little presence. This was followed by a presentation of the most important aspects of implementation and all the relevant data management content of Digital Twins. Finally, the benefits and challenges were discussed in order to show where Digital Twins are already worthwhile and where barriers still exist.
To integrate and benefit from Digital Twins in your own business, all these aspects are essential and the awareness needs to be raised. The challenges of integrating Digital Twins into business range from technological barriers (which will be addressed in further research) to organisational and cultural challenges that need to be addressed in other ways. Digital Twins are evolving and being used in more and different areas, so it is a very dynamic issue.
Both research questions were answered. The current state of the literature on Digital Twins was presented in detail. The methodology of how Digital Twins can be effectively used or implemented for production optimisation and what is necessary for this was also explained in detail.
This literature review provides a great general overview of Digital Twins. As there are many differences in the current literature, definitions can be very different. The topic of Digital Twins is not yet well researched, the paper thus provides a very good introduction and a short, informative and comprehensive overview of Digital Twins. The paper can also be of great help for future research as it shows and explains far-reaching and comprehensive information.

References

Agnusdei, G. P., Elia, V., and Gnoni, M. G. (2021). A classification proposal of digital twin applications in the safety domain. *Computers & Industrial Engineering*, 154, 107137. doi: 10.1016/j.cie.2021.107137.

Boschert, S., Rosen, R. (2016). Digital Twin—The Simulation Aspect. In: Hehenberger, P., Bradley, D. (eds) *Mechatronic Futures*. Springer, Cham. doi: 10.1007/978-3-319-32156-1_5.

Boyes, H., Watson, T. (2022) Digital twins: An analysis framework and open issues, *Computers in Industry*, Volume 143, doi: 10.1016/j.compind.2022.103763.

Bouloiz, H., Garbolino, E., Tkiouat, M., and Guarnieri, F. (2013). A system dynamics model for behavioral analysis of safety conditions in a chemical storage unit. *Safety Science*, 58, 32–40. doi: 10.1016/j.ssci.2013.02.013.

Chabanet, S., El-Haouzi, H.B., Morin, M., Gaudreault, J. and Thomas, P. (2023). Toward digital twins for sawmill production planning and control: benefits, opportunities, and challenges, *International Journal of Production Research*, 61:7, 2190-2213, doi: 10.1080/00207543.2022.2068086.

Chang, Y., Khan, F., and Ahmed, S. (2011). A risk-based approach to design warning system for processing facilities. *Process Safety and Environmental Protection*, 89(5), 310–316. doi: 10.1016/j.psep.2011.06.003.

Cimino, C., Negri, E., and Fumagalli, L. (2019). Review of digital twin applications in manufacturing. *Computers in Industry*, 113, 103130. doi: 10.1016/j.compind.2019.103130.

Fuller, A., Fan, Z., Day, C., and Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*, 1–1. doi: 10.1109/access.2020.2998358.

Glaessgen E., Stargel D. (2012). The digital twin paradigm for future NASA and US Air Force vehicles. 53rd *AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA 1818.*

Grieves, Michael. (2014). Digital Twin: Manufacturing Excellence through Virtual Factory Replication.

Grieves, Michael. (2016). Origins of the Digital Twin Concept. doi: 10.13140/RG.2.2.26367.61609.

Grieves, M., and Vickers, J. (2016). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. Transdisciplinary Perspectives on Complex Systems, 85–113. doi: 10.1007/978-3-319-38756-7_4.

Jones, D., Snider, C., Nassehi, A., Yon, J., and Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*. doi: 10.1016/j.cirpj.2020.02.002.

Klostermeier, R., Haag, S., Benlian, A. (2019). Digitale Zwillinge – Eine explorative Fallstudie zur Untersuchung von Geschäftsmodellen. In: *Meinhardt, S., Pflaum, A. (eds) Digitale Geschäftsmodelle* – Band 1. Edition HMD. Springer Vieweg, Wiesbaden. doi: 10.1007/978-3-658-26314-0_15.

Korotkova, N., Benders, J., Mikalef, P. and Cameron, D. (2023) Maneuvering between skepticism and optimism about hyped technologies: Building trust in digital twins, *Information and Management*, Volume 60, Issue 4, doi: 10.1016/j.im.2023.103787.

Kunath, M., and Winkler, H. (2018). Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process. *Procedia CIRP*, 72, 225–231. doi: 10.1016/j.procir.2018.03.192.

Leng, J., Zhou, M., Xiao, Y., Zhang, H., Liu, Q., Shen, W., Su, Q., Li, L. (2021) Digital twins-based remote semi-physical commissioning of flow-type smart manufacturing systems, *Journal of Cleaner Production*, Volume 306, doi: 10.1016/j.jclepro.2021.127278.

Li, J., Tao, F., Cheng, Y., and Zhao, L. (2015). Big Data in product lifecycle management. *The International Journal of Advanced Manufacturing Technology*, 81(1-4), 667–684. doi: 10.1007/s00170-015-7151-x.

Lim, K.Y.H., Zheng, P. and Chen, CH. (2020) A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing* 31. doi: 10.1007/s10845-019-01512-w.

Liu, Y. et al., "A Novel Cloud-Based Framework for the Elderly Healthcare Services Using Digital Twin,", *IEEE Access*, vol. 7, pp. 49088-49101, 2019, doi: 10.1109/ACCESS.2019.2909828.

Liu, Z., Meyendorf, N., and Mrad, N. (2018, April). The role of data fusion in predictive maintenance using digital twin. *AIP Conference Proceedings*, Vol. 1949, No. 1, p. 020023.

Ma, X., Tao, F., Zhang, M., Wang, T., and Zuo, Y. (2019). Digital twin enhanced human-machine interaction in product lifecycle. *Procedia CIRP*, 83, 789–793. doi: 10.1016/j.procir.2019.04.330.

Mandolla, C., Petruzzelli, A. M., Percoco, G.,and Urbinati, A. (2019). Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry. *Computers in Industry*, 109, 134–152. doi: 10.1016/j.compind.2019.04.011.

Moi, T., Cibicik, A., and Rølvåg, T. (2020). Digital Twin Based Condition Monitoring of a Knuckle Boom Crane: an Experimental Study. *Engineering Failure Analysis*, 104517. doi: 10.1016/j.engfailanal.2020.104517.

Negri, E., Fumagalli, L., and Macchi, M. (2017). A Review of the Roles of Digital Twin in CPS-based Production Systems. *Procedia Manufacturing*, 11, 939–948. doi: 10.1016/j.promfg.2017.07.198.

Perno, M., Hvam, L., Haug, A. (2022) Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers, *Computers in Industry*, Volume 134, doi: 10.1016/j.compind.2021.103558.

Psarommatis, F. and May, G. (2022a) A standardized approach for measuring the performance and flexibility of digital twins, *International Journal of Production Research*, doi: 10.1080/00207543.2022.2139005.

Psarommatis, F. and May, G. (2022b) A literature review and design methodology for digital twins in the era of zero defect manufacturing, *International Journal of Production Research*, doi: 10.1080/00207543.2022.2101960.

Reim, W., Andersson, E. and Eckerwall, K. (2023) Enabling collaboration on digital platforms: a study of digital twins, *International Journal of Production Research*, 61:12, 3926-3942, doi: 10.1080/00207543.2022.2116499.

Rosen, R., von Wichert, G., Lo, G., and Bettenhausen, K. D. (2015). About The Importance of Autonomy and Digital Twins for the Future of Manufacturing. IFAC-PapersOnLine, 48(3), 567–572. doi: 10.1016/j.ifacol.2015.06.141.

Saracco, R. (2019) "Digital Twins: Bridging Physical Space and Cyberspace", *Computer*, vol. 52, no. 12, pp. 58-64, doi: 10.1109/MC.2019.2942803.

Schleich, B., Anwer, N., Mathieu, L., and Wartzack, S. (2017). Shaping the digital twin for design and production engineering. *CIRP Annals*, 66(1), 141–144. doi: 10.1016/j.cirp.2017.04.040.

Semeraro, C., Lezoche, M., Panetto, H., and Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. *Computers in Industry*, 130, 103469. doi: 10.1016/j.compind.2021.103469.

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., Wang, L., 2012. Modeling, Simulation, Information Technology & Processing Roadmap. *National Aeronautics and Space Administration*.

Suhail, S., Malik, S.U.R., Jurdak, R., Hussain, R., Matulevičius, R., Svetinovic, D. (2022) Towards situational aware cyber-physical systems: A security-enhancing use case of blockchain-based digital twins, *Computers in Industry*, Volume 141, doi: 10.1016/j.compind.2022.103699.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., and Sui, F. (2017). Digital twin-driven product design, manufacturing and service with big data. The *International Journal of Advanced Manufacturing Technology*, 94(9-12), 3563–3576. doi: 10.1007/s00170-017-0233-1.

Tuegel, E. J., Ingraffea, A. R., Eason, T. G., and Spottswood, S. M. (2011). Reengineering Aircraft Structural Life Prediction Using a Digital Twin. *International Journal of Aerospace Engineering*, 2011, 1–14. doi: 10.1155/2011/154798.

J. Vachálek, L. Bartalský, O. Rovný, D. Šišmišová, M. Morháč and M. Lokšík, "The digital twin of an industrial production line within the industry 4.0 concept," *2017 21st International Conference on Process Control (PC)*, Strbske Pleso, Slovakia, 2017, pp. 258-262, doi: 10.1109/PC.2017.7976223.

VanDerHorn, E., and Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. *Decision Support Systems*, 145, 113524. doi: 10.1016/j.dss.2021.113524.

van der Valk, H., Haße, H., Möller, F., Otto, B. (2022) Archetypes of Digital Twins. *Business & Information Systems Engineering* 64, 375–391. doi: 10.1007/s12599-021-00727-7.

van Dinter, R., Tekinerdogan, B., Catal, C. (2023) Reference architecture for digital twin-based predictive maintenance systems, *Computers and Industrial Engineering*, Volume 177, doi: 10.1016/j.cie.2023.109099.

Vieira, J., Poças Martins, J., Marques de Almeida, N., Patrício, H., Gomes Morgado, J. (2022) Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins. *Sustainability* 14. doi: 10.3390/su14127060.

Villa, V., Paltrinieri, N., Khan, F., and Cozzani, V. (2016). Towards dynamic risk analysis: A review of the risk assessment approach and its limitations in the chemical process industry. *Safety Science*, 89, 77–93. doi: 10.1016/j.ssci.2016.06.002.

Wanasinghe, T. R. et al., "Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges,", *IEEE Access*, vol. 8, pp. 104175-104197, 2020, doi: 10.1109/ACCESS.2020.2998723.

Webster, J., Watson, R.T (2002) Analyzing the Past to Prepare for the Future: Writing a Literature Review. *MIS Quarterly*, 26.

Wolfswinkel, J.F., Furtmueller, E., Wilderom, C.P.M. (2013) Using Grounded Theory as a Method for Rigorously Reviewing Literature. *European Journal of Information Systems* 22, 45-55. doi: 10.1057/ejis.2011.51.

Zeb, A., Kortelainen, J., Rantala, T., Saunila, M., Ukko, J. (2022) On the alleviation of imminent technical and business challenges of long-lasting functional digital twins, *Computers in Industry*, Volume 141, doi: 10.1016/j.compind.2022.103701.