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Digital twins to increase sustainability throughout the system life cycle: a systematic literature review

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Abstract

Sustainability is not a new trend, but a mandatory measure for responsible and environmentally conscious use of resources. The digital transformation offers new potential in engineering and competitive advantages for companies through innovative technologies like the digital twin. Based on digital twins, products can be optimized, and new business models can be developed. Long-term added value is generated for manufacturing companies and customers. This paper explores the benefits of digital twins in the context of sustainability. Current challenges and use cases of digital twins are analysed.

Keywords: digital twin, sustainability, systematic literature review

1. Introduction

At a time when the world is increasingly focused on sustainability and environmental protection, the role of technology in promoting these goals is coming into focus. Rapid technological progress like Internet-of-Things, Artificial Intelligence (AI) or Digital Twin (DT) offers new opportunities and potential to develop and operate sustainable products (Argyroudis et al., 2022; Ramesohl et al., 2022). In addition, the complexity of these intelligent, technical systems (ITS) has already increased enormously in recent years due to the rising proportion of electronics and software (Gausemeier et al., 2019). This is reinforced by the increasing importance of sustainability over the entire product life cycle (Azevedo et al., 2010). On the one hand, many companies are faced with the compelling need for environmentally compatible and responsible use of existing resources. On the other hand, ensuring a balance between increasing sustainability requirements (e.g. from legislation) and economic efficiency is perceived as an increasing challenge (Dumitrescu et al., 2021). The Digital twin is a key concept that is becoming increasingly important in this regard. This technology not only offers the possibility of tracking and optimizing the entire life cycle of products in real time, but they also promise significant benefits in terms of resource efficiency, environmental protection, and competitiveness. The digital twin represents a digital image of a product, which captures, processes and networks selected information over the entire lifecycle for various applications. For example, the networking of development, production and operational data offers diverse opportunities that also have a significant impact on sustainability. Based on a systematic literature review, this article is dedicated to an in-depth examination of the potential benefits of a DT to enable sustainable product development and usage. Furthermore, the upcoming challenges for implementing DT for sustainable reasons and the various use cases of a DT in the context of sustainability are presented.

2. State of the research and related work

2.1. Sustainability

Sustainability has become a key issue for businesses, governments and society. The concept of sustainability encompasses the use of resources so that they not only meet the needs of the present generation, but also ensure the ability of future generations to meet their needs (Lélé, 1991). In this context, the current understanding divides sustainability into three dimensions - environmental, economic and social sustainability (Figure 1). Environmental sustainability is concerned with the responsible use of natural resources and the preservation of the environment for future generations, for example through measures to reduce pollution, the consideration of recyclable materials or the minimization of the carbon footprint. Economic sustainability aims to shape economic activities and processes in such a way that they promote long-term prosperity and stability, for example through the efficient use of resources. Social sustainability is about promoting justice, equality, and well-being in society. Socially sustainable development aims to reduce social inequalities, promote diversity and take into account the needs of all generations (Becker et al., 2015; Scholz et al., 2018). Integrating the aspects of the individual dimensions into product development is an essential step in the development and use of sustainable products (Eigner & Schäfer, 2014). During integration, measures in one dimension can have a direct impact on the others. The resulting conflicts of objectives must be taken into account during integration (Sulewski et al., 2018).

Figure 1. Three dimensions of sustainability based on (Becker et al., 2015; Scholz et al., 2018)

Numerous regulations require the development of sustainable products. The 17 UN Sustainable Development Goals (UN SDGs) were established by the United Nations (UN) in 2015. The UN SDGs aim to promote sustainable development at a global level and combine economic, social, and environmental aspects. The overarching goal of the SDGs can be summarized in four main dimensions: economic development, social inclusion, environmental protection and peace. By linking the dimensions together, the SDGs are intended to provide a coherent and integrative response to the complex challenges of our time in order to enable a sustainable and just future (United Nations, 2015). The European Green Deal is an initiative of the European Union (EU) that was presented in 2019. The aim is to create a modern, resource-efficient, and competitive economy. By 2050, net zero greenhouse gas emissions are to be achieved, economic growth is to be decoupled from resource use and the focus is to be on greater regional thinking (European Parliament, 2022). In March 2020, an action plan for the EU was presented in the form of the Circular Economy Action Plan. It shows the member states how they can actively implement national strategies and measures to integrate a circular economy. Companies are to be supported in the transition to a sustainable economic system (European Commission, 2023). A "digital product passport" is a key instrument mentioned in both strategy papers, which is intended to create transparency across the entire product life cycle. It makes it possible to manage and store all the necessary information and data for a product along the value chain. In this way, economic actors can access the information they need to operate in a climate-neutral and resource-efficient manner (Götz et al., 2021).
Overall, sustainability is a comprehensive concept that considers the interactions between the environment, society and the economy. In addition to a multitude of challenges, the concept also brings

opportunities for positive change. Through conscious action at an individual, corporate and political level and the use of innovative technologies, we can work together to help create a more sustainable future.

2.2. Digital Twin

The digital twin (DT) is a digital representation of a real product and captures, processes and networks selected information for various applications (Industrial Internet Consortium, 2023). The concept of the DT was first introduced in 2002 by Grieves (2002) In the context of product lifecycle management, this is described as a virtual space that contains data from the real product, analyses it and processes it back to the physical twin. A first definition of a DT was given by NASA in 2010. Here, the DT is described as a multi-physical simulation of a flying system, which considers physical models, sensor and fleet data, and maintenance history (Shafto et al., 2010). Over the years, a variety of definitions have been published in the context of the DT. Especially in the context of Industry 4.0 and technological advances such as the Internet of Things (IoT), a multitude of new possibilities for the digital twin in industry and research became possible. The Industrial Digital Twin Association (IDTA) defines the DT as a "digital representation that is sufficient to meet the requirements of a set of use cases". This contains characteristic features and the behavior of an asset in the Asset Administration Shell (AAS) (Industrial Digital Twin Association e.V., 2023). Other terms to be defined are the digital model, the digital shadow and the digital thread. The digital model is the virtual representation of a product or component that only exchanges data manually. The digital shadow differs from the digital model in that it creates an automated link from the real to the virtual world, thus mapping the virtual space of a certain system state. This means that changes to the real product are adopted directly. As soon as a fully automated connection exists between the real and virtual product, we speak of DT (Bauernhansl et al.; Kritzinger et al., 2018). The digital thread is a complete connection of the digital models of a product over the entire life cycle (Helu & Hedberg, 2015). Due to the wide range of digital twin approaches and definitions, there is a multitude of applications. Currently, there is no approach that shows the added value of a DT in the context of sustainability.

3. Methodology

3.1. Research design

The development and operation of sustainable products is one of the biggest challenges for companies. A large amount of information can be found in the literature. A systematic approach is required to find the relevant literature sources. The systematic literature review (SLR) approach is used in this paper to examine the current body of literature regarding the potential benefits for digital twins in the context of sustainability along the product lifecycle. Furthermore, the paper investigates which use cases of the digital twin concept in the sustainability context are listed in the literature and which implementation challenges exist. The procedure of the SLR is divided into three phases: planning, conduction and reporting (Kitchenham & Charters, 2007). In the planning phase of the review, specific research questions are defined and form the most important part of an SLR. Based on the research questions, the search string is defined at the beginning of the implementation phase of the review and focuses on the title, abstract and keywords of the existing literature. Subsequently, the relevant literature is identified and evaluated in terms of quality and relevance. The relevance of the identified paper was evaluated by two persons. Thus a subjective evaluation can be counteracted. Furthermore, further relevant literature cited in the identified literature was taken into consideration with the help of the backward search (Webster & Watson, 2002). In the subsequent reporting phase of the review, the results obtained are documented and the research questions are answered.

3.2. Research questions

Based on the problem analysis and the resulting challenges for companies to develop sustainable products and to use and manage the multitude of data, the innovative concept of a digital twin offers a possible approach. This gives rise to the following questions, which define the goals of SLR:

- *Is the digital twin concept a suitable technology for increasing sustainability along the product life cycle?*
- *What are the current challenges for the implementation of digital twins in the context of sustainability?*
- *Which current use cases of digital twins are relevant in the individual product lifecycle phases regarding sustainability?*

4. Digital Twin & sustainability

4.1. SLR research design

To answer the defined research questions and thus achieve the objective of the SLR, one search string is developed. To extract the relevant literature for enhancing sustainability through digital twins, two groups of terms were applied. In the first group, the terms "Sustainability" and "Sustainable" are used in combination with the terms "Digital Twin", "Digital Thread" and "Digital Shadow". The terms are linked with the Boolean operators AND and OR. The scientific database Scopus and the database IEEE were used for the literature search. No further terms were intentionally added so that the search would include all relevant papers and the topic of digital twins could be examined holistically in the context of sustainability.

Search string: *("Sustainability" OR "Sustainable") AND ("Digital Twin" OR "Digital Thread" OR "Digital Shadow")*

The review procedure is visualized in Figure 2. The defined search string resulted in a total number of 1232 relevant references (10/21/2023). The search in the Scopus database yielded 1151 results and 81 references were identified in IEEE. In the first step of the SLR, the results were examined for existing duplicates. In this process, 50 duplicates were identified. In the next step, the individual titles of the literature were reviewed to determine whether they were relevant to the topic of digital twins and sustainability. No papers were identified as relevant if they only addressed one of the two topics. Based on the title analysis, 380 relevant candidates were identified. In the third step, these were analysed for suitability for the three research questions based on the abstract. The result was 64 publications that consider the digital twin in the context of sustainability. In the final step, these 64 publications were subjected to a full-text analysis. Four additional publications were identified using the backward search described above. The result of the review is 29 publications that are relevant to the research questions.

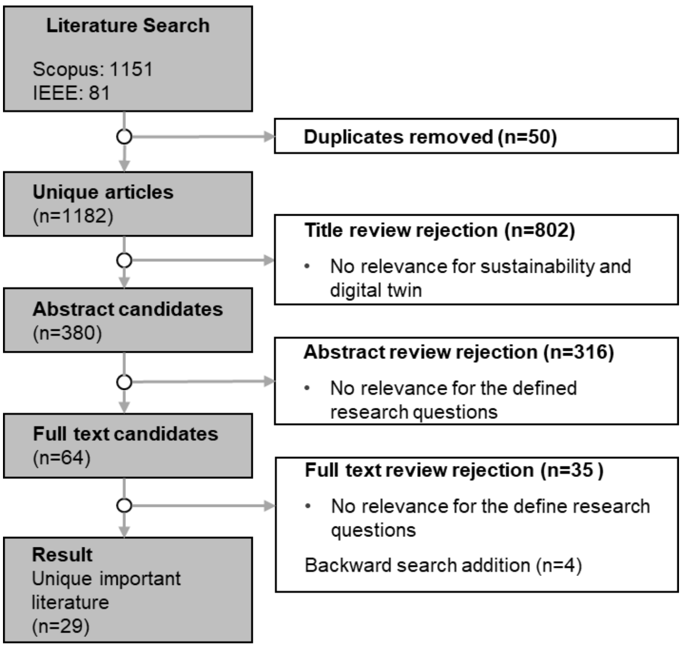

Figure 2. SLR research design for analysing the relevance of DT in the context of sustainability

4.2. General findings

The results of the systematic literature review show that DT is a suitable tool for companies to increase sustainability. The relevant literature sources prove the potential of DT for increasing sustainability and thus answer the first research question. The results are explained in more detail in 4.2.1. However, companies face several challenges when using DT for the development or use of sustainable products (4.2.2), such as the uniform implementation of DTs or poor data quality along the product life cycle. Furthermore, use cases for DT in the context of sustainability described in the literature are described and structured based on a product life cycle (4.2.3).

4.2.1. Main benefits of digital twins for more sustainability

The concept of a DT offers a multitude of possibilities for increasing sustainability through its characteristics. The digital twin enables a fully updated representation of the behavior of the intelligent technical system (ITS). The DT enables real-time mirroring of the ITS and comparison between historical and current data and builds the capability for system optimization through predictions based on simulation data (Barni et al., 2018; Hassan et al., 2023; Monteiro et al., 2023). In particular, the optimization potential through DT can help companies to increase the sustainability of the company and their products (Bellis & Denil, 2022). Integrated data management systems and the ability to capture the behavior and condition of products and individual components in real time improve the disassembly process and thus increase the reuse of valuable components and materials. DT also offers innovative ways to create KPIs for the decision-making process in terms of optimization, monitoring and the resulting minimization of energy and material resources. In terms of the circular economy, DT is therefore a useful tool for making sustainability-relevant data usable (Rocca et al., 2020). The potential of DT for achieving the UN Sustainability Goals is addressed in Hassani et al. (2022). For the manufacturing industry, the DT opportunity enables it to contribute to achieving the goals. Sustainable production, the possibility of predictions and sustainable data management through DTs have a direct added value for the realization of resilient and sustainable processes and products in the industrial environment.

Linking DTs with big data technologies offers potential in terms of data collection, prediction, and analysis along the product life cycle. In Ma et al., (2022), a framework for the integration of big data in DTs is presented to enable sustainable manufacturing. The use of DT in combination with AI increases the potential benefits, for example to enable the automated early identification of faults or damage (Argyroudis et al., 2022) or to improve the selection of recyclable materials. The use of ML in DTs increases the effectiveness and efficiency of manufacturing and the quality of the products produced. This results in cost reductions and an increase in a company's profits (Rojek et al., 2021). DT also offers companies additional opportunities to develop digitally sustainable business models. New business models in particular enable companies to promote environmental sustainability and increase their competitiveness at the same time (Rocca et al., 2020).

DT offers a wide range of advantages for increasing sustainability in companies. Features such as real-time data collection or the comparison of historical data with current data offer a high potential for optimization along the entire product life cycle. A detailed and holistic consideration of the potential benefits of DTs, particularly for product development, cannot be found in the literature. Furthermore, the use of DTs in combination with AI must be further investigated in this context. The potential for different sectors such as the automotive industry or plant and mechanical engineering cannot be found in the literature. Furthermore, the potential for sustainable business models based on DT is only slightly examined in the literature. In addition, the use of a DT and the associated optimization potential with regard to the use of resources or the facilitation of sustainable business models is of particular interest for the ecological and economic dimension of sustainability and must be investigated further.

4.2.2. Challenges in the implementation of a digital twin in the context of sustainability

The different definitions of DT described above, and the wide variety of application areas offer great potential for economic, environmental and social sustainability. Nevertheless, this and the increasing complexity of ITS make the development of DT more difficult. There is a lack of standardization measures and holistic process models for the uniform design and implementation of DT. One possible

approach is to categorize the interaction between DTs. A distinction is made here between a product DT, production DT and a factory DT. However, the different physical systems place different demands on the DT, including in the context of sustainability.
Other challenges include the need for real-time data flow and the need for advanced analytics for decision making. The data quality of the relevant data is also a challenging factor, which is often insufficient for the use of DT. This results in incorrect simulations and analyses (Hassan et al., 2023; Huang et al., 2021; Kamble et al., 2022). Furthermore, data must be anonymized for further use for data protection reasons. Financial and cybersecurity aspects must not be neglected either (Carvalho & Da Silva, 2021; Kies et al., 2022)
In addition to the general challenges for the implementation of DTs, their use in the context of sustainability entails a further level of complexity. DTs mean additional energy consumption, which must be considered in the development and use of DTs. Large amounts of data are often required to use DTs precisely. In addition to the high energy consumption and large amounts of data, additional costs are also caused by the development. The challenge is to recognize the value of a DT. As soon as the development and usage costs exceed the value generated by the DT, the purpose of the DT must be reconsidered (Bellis & Denil, 2022).
The identified literature only describes a small number of challenges for the implementation of DT in the direct context of sustainability. General topics such as the high number of definitions or the lack of standards and sustainability-related standards such as the increasing energy demand for the use of DT are addressed in passing. The challenges for the use of DT for sustainable fields of application should be clearly identified and investigated. The trade-offs between the dimensions of sustainability must be taken into account in the development of DT.

4.2.3. Identification of current use cases

Figure 3 shows the use cases identified in the relevant literature. These were clustered according to the individual life cycle phases of an ITS, starting with market and product planning, through the development phases (requirements, system design, verification, and validation) to the use of the product and the subsequent the End-of-Life of the ITS.

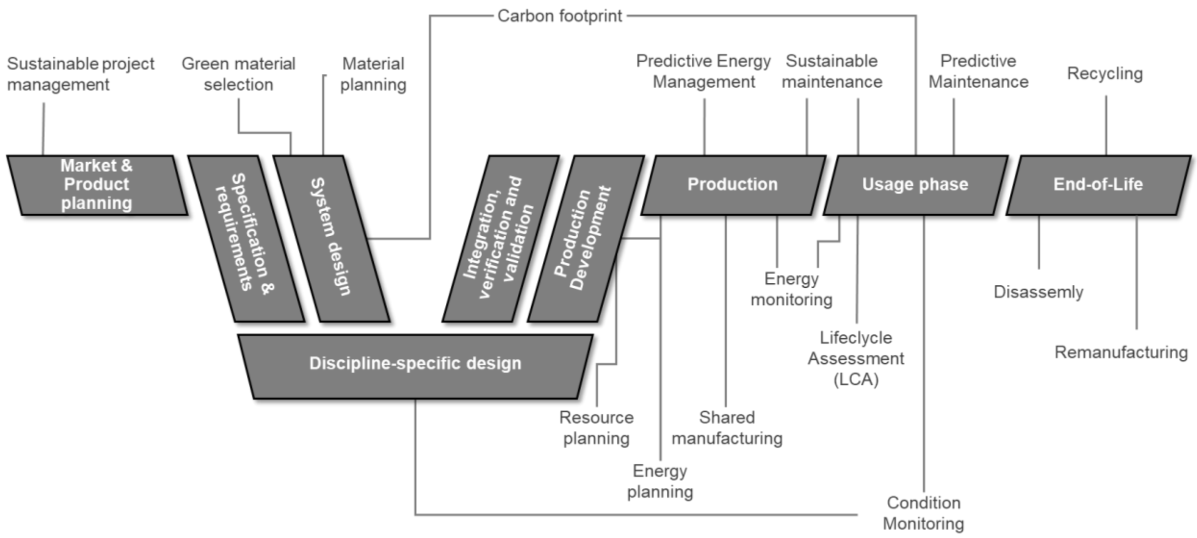

Figure 3. Clustering of sustainable DT use cases along the product life cycle

Use cases can already be found in the literature in the early phases of the product life cycle. Chakrabortty et al. (2019) uses DT for sustainable project management. DT can already take into account ecological parameters in addition to emerging costs when planning projects and thus create fewer disruptions and sustainable project plans.
In terms of product development, Xiang et al. (2019) describes DT in the context of sustainable material selection. Simulations using DT are able to predict the behavior of products along the product life cycle

and thus sustainably influence the selection of possible materials in development. Sustainability-relevant data such as energy and CO2 data or recycling potential can thus be considered at an early stage when selecting materials.
In the area of production, DT is used for energy and resource planning. In (Ball & Badakhshan), the DT supports the decision-making process for the implementation of energy-intensive production steps. When analyzing, DT must always take costs, energy consumption and production capacities into account. Senna et al. (2020) describes the use of DT for energy forecast management. The approach models the individual components of the overall system, integrates data from the real and virtual world and enables optimized energy use and an improvement in environmental impact based on analyses and simulation. In Hassan et al. (2023) and Huang et al. (2021) the DT is used for predictive maintenance. The aim here is to reflect the behavior of a product, to identify possible damage to the product and critical components that would cause the product to fail. These predictive maintenance systems which are presented in the literature are often inaccurate or incorrect. This may be due to poor data quality or a lack of training data for the DT. The approach in G. Wang et al. (2021) uses the DT for service model to increase the effectiveness and efficiency of production facilities by allocating resources to shared production facilities in the sense of the sharing economy.
Looking at the use phase of a product, the literature shows sustainable use cases. In Barni et al. (2018; Rückert et al. and Wellsandt et al. (2017), DT is studied in the context of a semi-automated, modular, and scalable approach to lifecycle assessment (LCA). For a robust LCA, high data quality and accuracy is needed to obtain a meaningful result. Often, data must be prepared in a complex way beforehand. In addition, the implementation is currently associated with a lot of effort. The use of a DT improves the quality and accuracy of the data by collecting real-time data, such as energy consumption or CO_2 data. Huang et al. (2021) describes a major added value of the DT use cases of condition monitoring and predictive maintenance. Especially in combination with artificial intelligence (AI), predictions about possible failures and faults can be made at an early stage in order to extend the product's lifespan. Rojek et al. (2021) describe a DT system that enables different use cases in combination with machine learning (ML) along the product life cycle. With the help of decision trees, large amounts of data are used to draw conclusions, for example about the sustainable use of materials in the early stages of product development. The combination of stored knowledge in DT and the use of real-time product data using sensors enables an optimized usage phase and predictive maintenance.
The end-of-life phase is considered in the literature in connection with R-strategies such as recycling, remanufacturing or reuse. Mügge et al. (2023) uses the DT to analyze information along the product life cycle to make the right choice of R-strategies and thus contributes directly to a circular economy. Furthermore, the DT enables the establishment of circular economy key performance indicators (KPIs) such as the remaining useful lifetime or the assemblability. Y. Wang et al. (2020) describes a DT approach for improving the remanufacturing of products. Intelligent technology is used to collect the relevant information, which DT uses to predict and optimize the remanufacturing of products over several life cycles.
In summary, the literature already includes a large number of DT use cases for greater sustainability along the product life cycle. The SLR identified many use cases, particularly in manufacturing. Initial DT approaches are also available in the early phases of the life cycle to support companies' sustainability efforts. Nevertheless, the SLR shows that there is great potential here, but few use cases have been identified. Especially in product development, DT can have an early influence on the sustainable design of products. When considering the use and end-of-life phase, DT can have a significant influence due to real-time data acquisition and predictions. The identified use cases such as energy monitoring, material planning and recycling primarily take environmental sustainability into account. Economic sustainability is considered in the use case of shared manufacturing or early material planning, while the social sustainability aspect is treated more lightly.

5. Conclusion and outlook

The scientific contribution of this paper is to analyses the influence and suitability of the digital twin (DT) concept for increasing sustainability. The results of the systematic literature review show the potential of DT in the context of sustainability, which challenges exist in the implementation of DT and addresses existing DT use cases in research and industry.

The results of the study show that DT has great potential for increasing sustainability and is therefore a suitable technology for increasing sustainability along the product life cycle. The characteristics of a DT, such as real-time data collection, the integration of a variety of data along the product life cycle or the analysis of historical data, enable the optimization of products and processes and a simultaneous reduction of costs and negative environmental impacts. The DT is a suitable tool to support companies in complying with legal requirements and achieving the UN Sustainability Goals. Nevertheless, this article shows that the potential for DT for product development in particular is not sufficiently addressed in the literature.

The study reveals a number of challenges that make the implementation of a DT difficult. There is no uniform standard or procedure for the implementation and use of DTs in the context of sustainability. Furthermore, a large amount of data is necessary to be able to make accurate analyses and predictions based on DTs. This is made increasingly difficult by a lack of data quality. The increasing complexity resulting from the use of DTs, the multitude of definitions and application options make implementation more difficult. The identified use cases have a strong focus on production. In particular, methods and approaches for the implementation of DT are presented in relation to energy management and energy monitoring. Initial approaches can be found in the literature in the early phases like product development and the end-of-life phase of the ITS life cycle, but there is a need for research both in terms of identifying further use cases and for the use of DTs in existing processes such as recycling or the reuse of products. The combination with AI like the machine learning approach needs to be investigated. The end-of-life phase and the influence of a DT should also be examined more closely. This article also shows the added value of a DT in the utilization phase. Approaches for supporting a DT in carrying out an LCA and predicting faults and maintenance can be found in the literature. Further research is needed to ensure that these approaches deliver real benefits for companies in terms of sustainability. With regard to legal requirements for innovative instruments such as a digital product passport, the research does not reveal any approach. The potential of a DT for this use case must be demonstrated in detail. Furthermore, the use of DT in product lifecycle management (PLM) has been addressed in the identified literature. The exact influence of PLM on increasing sustainability needs to be the subject of research. Considering the definition of sustainability in chapter 2.1, the identified advantages and properties of a DT can bring sustainable added value along the product life cycle. In particular, the DT can support the achievement of ecological and economic goals through targeted applications.

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