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Impact of Digital Twins on Sustainability of SMEs: A Systematic Literature Review

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KEYWORDS

- Digital Twins
- Sustainability
- SMEs
- Systematic Literature Review

ABSTRACT

This systematic literature review (SLR) investigates the impact of Digital Twins (DTs) on the environmental, economic, and social dimensions of sustainability in small and medium-sized enterprises (SMEs). SMEs, making up about 90% of global businesses, face challenges in adopting sustainable practices due to limited resources. DTs, as virtual representations of physical systems, provide opportunities for SMEs to optimize processes and achieve sustainability goals. Using the PRISMA methodology, a structured search was conducted, targeting peer-reviewed articles published between 2015 and 2024. The findings show that DTs enable cost reductions, improved resource efficiency, and enhanced working conditions. However, high initial costs and technical complexity pose significant barriers for SMEs. The review also highlights gaps in long-term studies on ecological benefits and socio-economic impacts. The study concludes that while DTs offer considerable potential for advancing sustainability in SMEs, strategic implementation and support mechanisms are essential for overcoming existing challenges.

JEL-codes: L25, L26, L60, M15, O33, Q56

KULCSSZAVAK

- Digitális ikrek
- fenntarthatóság
- KKV-k
- szisztematikus szakirodalmi áttekintés

ABSZTRAKT

A digitális ikrek hatása a kis- és középvállalkozások fenntarthatósági teljesítményére: szisztematikus szakirodalmi áttekintés | Ez a szisztematikus szakirodalmi áttekintés (SLR) a digitális ikrek (DT) hatását vizsgálja a fenntarthatóság környezeti, gazdasági és társadalmi dimenzióira a kis- és középvállalkozásokban (kkv-k). A globális vállalkozások mintegy 90%-át kitevő kkv-k a korlátozott erőforrások miatt kihívásokkal szembesülnek a

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fenntartható gyakorlatok átvételében. A DT-k, mint a fizikai rendszerek virtuális reprezentációi, lehetőséget nyújtanak a kkv-k számára a folyamatok optimalizálására és a fenntarthatósági célok elérésére. A PRISMA módszertan alkalmazásával strukturált keresést végeztünk, amely a 2015 és 2024 között megjelent, lektorált cikkekre irányult.
Az eredmények azt mutatják, hogy a DT-k lehetővé teszik a költségcsökkentést, az erőforrás-hatékonyság javítását és a munkakörülmények javítását. A magas kezdeti költségek és a technikai összetettség azonban jelentős akadályokat jelentenek a kkv-k számára. Az áttekintés rávilágít az ökológiai előnyökre és a társadalmi-gazdasági hatásokra vonatkozó hosszú távú tanulmányok hiányosságaira is. A tanulmány arra a következtetésre jut, hogy bár a DT-k jelentős lehetőségeket kínálnak a kkv-k fenntarthatóságának előmozdítására, a stratégiai végrehajtás és a támogatási mechanizmusok elengedhetetlenek a meglévő kihívások leküzdéséhez.

JEL-kód: L25, L26, L60, M15, O33, Q56

Introduction

Achieving sustainability goals is especially challenging for small and medium-sized enterprises (SMEs), which make up about 90% of the world's companies and contribute significantly to global value creation (Chen et al., 2022). According to Marshall (1999), SMEs are believed to contribute around 60% of carbon dioxide emissions. SMEs are also responsible for 60% to 70% of industrial pollution worldwide (Calogirou et al., 2010). SMEs often have limited financial, technical and human resources, which makes it difficult for them to adopt sustainable technologies and processes (Bigliardi & Galati, 2017). At the same time, they are under pressure from stakeholders and regulators to make their production processes more sustainable (Baah et al., 2021; Ernst et al., 2022). In this context, an increasing number of blog posts, advertisements and examples from various companies are emerging online, that claim that digital technologies offer promising opportunities for SMEs to achieve their sustainability goals (Altintop, 2020; Bundesnetzagentur, 2024; European DIGITAL SME Alliance, 2024).

The aim of this systematic literature review (SLR) is to give a structured overview of the existing scientific contributions on the influence of Digital Twins (DTs) on the ecological, economic and social sustainability of SMEs and provide a solid foundation for future research and practical applications. The following central research question was chosen to serve this objective:

What is the current state of literature regarding the economic, environmental and social impact of Digital Twins on SMEs?

To answer the research question, a SLR was carried out in the scientific databases SCOPUS, Web of Science (WoS) and IEEE Xplore according to the SALSA framework model.

This paper is structured in six sections, as outlined in *Figure 1*:

Figure 1 – Structure of the Paper
Source: Own illustration (2024)

In Section 1, the paper outlines the importance of sustainability for SMEs, the challenges they encounter, and the transformative potential of DTs. It establishes the research objectives and formulates the central research question. Section 2 provides a concise theoretical background on SMEs, the dimensions of sustainability, and DTs. Section 3 describes the SLR methodology, emphasizing the SALSA framework and PRISMA protocol. Section 4 presents the review findings, focusing on the economic, environmental, and social impacts of DTs on SMEs, while synthesising and analysing results, identifying patterns, and addressing research gaps. Section 5 concludes key insights and highlights contributions.

Research Background

The following chapter provides a brief overview of the three most important research areas: SMEs, sustainability and Digital Twins.

Small and Medium-sized Enterprises

SMEs are defined based on a combination of criteria, including employee count, revenue, and organizational structure, with the specific thresholds varying globally. In the European Union, SMEs are categorized as enterprises with less than 250 employees and an annual turnover below €50 million or an annual balance sheet total less than €43 million (European Commission, 2003). SMEs represent about 90% of global enterprises, contributing to economic growth, job creation, and innovation (Chen et al., 2022).

Sustainability in a Corporate Context

As shown in *Figure 2*, Corporate sustainability entails balancing economic growth, environmental stewardship, and social responsibility, known as the Triple Bottom Line (TBL) (Elkington, 2004).

Figure 2 – Three Pillars of Sustainability
Source: Own illustration, based on Elkington (2004)

Environmental Sustainability focuses on reducing ecological footprints by minimizing waste, emissions, and resource consumption (World Commission on Environment and Development, 1987). Economic sustainability pertains to the financial viability and competitiveness of production processes. It involves cost reduction, efficiency improvements, and innovation to maintain profitability over time (Dyllick & Hockerts, 2002). Social Sustainability relates to the well-being of employees and communities. It encompasses fair labour practices, workplace safety, and community engagement (McKenzie, 2004). According to Marshall (1999), SMEs are estimated to contribute approximately 60% of carbon dioxide emissions. They are also responsible for 60% to 70% of industrial pollution worldwide (Calogirou et al., 2010). SMEs often face constraints in financial, technical, and human resources, which makes it challenging for them to adopt sustainable technologies and processes (Bigliardi & Galati, 2017).

Compared to large corporations, SMEs often face limited financial, technical and human resources, which makes it difficult for them to adopt sustainable technologies and processes (Bigliardi & Galati, 2017).

Digital Twins: Definition and Development

The term Digital Twin was first introduced by Michael Grieves in 2003 and describes a virtual representation of a physical object or system that reflects its properties and behaviour in real or near real time. DTs enable bidirectional communication between the physical and digital worlds, whereby data from the real system is transferred to the virtual model and vice versa. This technology is based on the integration of sensor technology, data analysis and simulation techniques to enable a comprehensive understanding and optimised control of systems (M. Grieves & Vickers, 2017).

DTs generally contribute to sustainability by offering economic, environmental, and social benefits within the TBL framework (Kamble et al., 2022).

Research Design and Methodology

A Systematic Literature Review is acknowledged as a fundamental element of the systematic review process. This methodology offers several advantages that are crucial for answering the underlying research question. An SLR provides an overview of the current state of research, and the conclusions to be drawn from it, including identified research gaps (Feak & Swales, 2009; Tranfield et al., 2003). SLRs enhance transparency, reproducibility, and bias minimization, ensuring valid results and a solid basis for future studies (Kitchenham & Charters, 2007; Petticrew & Roberts, 2006). This is particularly important in a dynamic and rapidly growing field of research such as DTs, where the quality and relevance of the literature can vary greatly. Furthermore, an SLR allows for the integration of different perspectives on the economic, environmental and social impact of DTs on SMEs, leading to a more holistic understanding of the topic. By considering the literature from different disciplines and contexts, patterns and knowledge gaps can be identified that are relevant for further research (Fink, 2010).

In order to minimize subjectivity and to ensure a structured research process, the literature review follows the four steps of the SALSA framework model, developed by Grant and Booth (2009) shown in *Figure 3*:

- Databases
- Keywords

- PRISMA Protocol:
- Identification
- Screening
- Eligibility
- Inclusion

- Review of full papers
- Grouping of Papers

- Thematic Analisys
- Identification of themes and gaps

Figure 3 – SALSA Framework Model

Source: Own illustration, based on Grant and Booth (2009)

In the initial search phase, relevant literature is comprehensively identified using well-known databases, to gather a wide range of materials on the topic. The appraisal phase then critically evaluates the quality and relevance of these sources to ensure only credible studies are included, excluding unreliable research. Following established practices (Bathaei & Štreimikienė, 2023), this paper employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol at the appraisal stage within the SALSA framework. PRISMA ensures transparent and reproducible documentation of decisions regarding study selection and evaluation. The evaluation proceeds in four steps: In the identification step, all sources are identified using a keyword search. In the screening step, inclusion and exclusion criteria are defined and the subsequently identified papers are reviewed according to title and abstract. Duplicates are then removed. In step 3, the eligibility step, the documents identified in step 2 are compared in terms of their content for relevance to the research question. In the last step, the documents that have now been identified as final are used for the synthesis phase in the SALSA process (Moher et al., 2009). In the synthesis phase, the information from the appraised studies is combined and organized to highlight patterns, themes, and insights. It involves integrating findings from multiple studies to provide a cohesive understanding of the topic.

The final analysis stage involves interpreting the synthesized data, extracting conclusions, and answering the research questions to allow for an in-depth understanding of the implications, gaps, and trends in the literature, providing a basis for further research or practical applications.

Research Results

The systematic application of the SALSA framework provides the results outlined in the following chapters.

Search

A structured literature search was conducted to systematically investigate the current state of research on the research question defining key terms and synonyms to ensure comprehensive coverage.

Search Terms and Keywords

To cover the central topics of the research question, the primary search terms 'Digital Twins', 'Sustainability', 'SMEs' were defined. To capture the influence of DTs on the dimensions of sustainability more precisely, secondary terms were defined to describe the specific aspects of sustainability: To analyse the economic influence of DTs, terms such as 'economic*', 'economic impact', 'cost reduction', 'productivity' and 'operational efficiency' were used.

For the environmental dimension of sustainability, terms such as 'ecologic*', 'environment*', 'sustainable development', 'environmental impact', 'resource efficiency', 'energy efficiency' and 'carbon footprint' were applied. To capture the social dimension, terms such as 'social impact', 'workforce', 'employee well-being' and 'social responsibility' were included.

Boolean operators (AND, OR) were used to combine these terms to effectively identify relevant studies.

Selection of Database

The SLR was conducted in the scientific databases Scopus, WoS and IEEE Xplore. Google Scholar was deliberately not included for methodological reasons. Although Google Scholar enables a broad spectrum of literature, it only fulfils the main requirements of a systematic review to a limited extent, such as transparency, reproducibility and consistency of search strategies. In particular, the unclear selection and display principles of the source selection, the limited use of Boolean operators and the dynamic presentation of results make a structurally and methodologically valid study difficult. Scopus, WoS and IEEE Xplore allow this controlled, documentable and qualitatively assured search, which guarantees traceability and comparability of the results. Additionally, the three databases offer an extensive collection of scientific articles in the fields of technology, economics and sustainability and are therefore suitable resources for systematic literature analyses and other academic research in these fields. Since the guidelines of all used databases require abstracts of research articles to be in English, the keywords were formulated exclusively in English (van Weijen, 2012).

The search queries were carried out using the defined search terms and Boolean operators for both databases to ensure a consistency of the search results.

Inclusion and Exclusion criteria

An exclusion criterion was set regarding the publication date to ensure that the results of the SLR reflect current trends and technological developments. Studies published before 2015 were excluded, as the term 'Digital Twin' gained increased importance in scientific publications around 2015 (M. W. Grieves, 2023) and the United Nations adopted the Sustainable Development Goals in 2015, making sustainability one of the global priorities (United Nations General Assembly, 2015). Moreover, articles not available in German or English were excluded to secure that the search results could be used in the analysis.

Appraisal

Table 1 documents the applied steps of the PRISMA methodology in the literature review and specifies the number of studies included and excluded at each stage.

Table 1 – Evaluation of the literature according to the PRISMA process

Step	*Search Categories*	*Exclusion*	*Total*			
			SCOPUS	WoS	IEEE	Σ
	Step 1: Identification					
Keyword Search	*Digital Twin AND Economic Sustainability AND SMEs*		*64*	22	*0*	*86*
	Digital Twin AND Environmental Sustainability AND SMEs		*89*	*44*	*66*	*199*
	Digital Twin AND Social Sustainability AND SMEs		51	*20*	*26*	*97*
	Total		**204**	***86***	***92***	***382***
	Step 2: Screening					
Application of Inclusion and Exclusion Criteria	*Digital Twin AND Economic Sustainability AND SMEs*	**-** 19	45	22	0	67
	Digital Twin AND Environmental Sustainability AND SMEs	*-31*	*68*	*42*	*58*	*168*
	Digital Twin AND Social Sustainability AND SMEs	*-18*	*34*	*20*	*25*	*79*
	Total	***- 68***	***147***	***84***	***83***	***314***
Review of Title and Abstract	*Digital Twin AND Economic Sustainability AND SMEs*	*- 15*	*37*	*15*	0	52
	Digital Twin AND Environmental Sustainability AND SMEs	*- 53*	*49*	*24*	42	115
	Digital Twin AND Social Sustainability AND SMEs	*- 25*	*25*	*14*	15	54
	Total	**- 93**	**111**	**53**	**57**	**221**
Removal of Duplicates / Non-accessible documents	*All Categories*	**-** 157	64			
	Step 3: Eligibility					
Review of Content	*All Categories*	*- 21*	43			
	Step 4: Inclusion					
	Total		**43**			

Source: Own research (2024)

In the initial identification step, a keyword-based search was conducted across the databases, SCOPUS, WoS and IEEE Xplore, using terms related to DTs and different aspects of sustainability, specifically economic, environmental, and social sustainability in the context of SMEs. This search identified a total of 382 studies, with 204 coming from SCOPUS, 86 from WoS and 92 from IEEE Xplore.

During the screening step, the first step was the application of inclusion and exclusion criteria, refining the selection based on relevance regarding publication dates, language and publication type. This led to the removal of 68 studies, leaving 314 studies in total, of which 147 were from SCOPUS, 84 from WoS and 83 from IEEE Xplore. The second part of the screening process involved a detailed review of titles and abstracts to ensure further relevance regarding the research question. This led to the exclusion of 15 studies in the economic sustainability category, leaving 52 studies, of which 37 came from SCOPUS, 15 from WoS and 0 from IEEE Xplore. For environmental sustainability, 53 studies were excluded, leaving 115 studies, with 49 from SCOPUS, 24 from WoS and 42 from IEEE Xplore. In the social sustainability category, 25 studies were excluded, resulting in a total of 54 studies, with 25 from SCOPUS, 14 from WoS and 15 from IEEE Xplore. The final step of the screening process involved the identification and elimination of 107 duplicate entries from the results of the individual search terms and databases, and the exclusion of 50 inaccessible documents. This step was only carried out at this stage to adequately display the results of the individual search queries for each database and each sustainability dimension.

In the eligibility step, a thorough review of the full content of the remaining studies was conducted to ensure they met the inclusion criteria. The review criteria focussed on the relevance to the research question, whether the document addresses the dimensions of economic, environmental and social sustainability and examines the impact of DTs on the sustainability of SMEs. In addition, it was checked whether the use of DTs was explicitly addressed in the context of SMEs. The lack of applicability of these criteria led to the exclusion of 21 papers. However, it turned out that almost all the studies did not directly examine the sustainability aspect as a primary factor, but rather that sustainability was a side effect of the research analysed in the study.

Nevertheless, in the final inclusion step of the appraisal process, 43 studies were selected for detailed analysis, as they were most closely aligned with the research focus on DTs and their implications for sustainability in SMEs. These studies still can provide a basis for the synthesis and enable an answer to the research question.

Synthesis

A total of 23 of the 43 papers (approx. 53 %) are published in scientific journals. This shows that more than half of the studies have been validated by peer review and meet scientific standards for methodological rigour. 18 of the papers (approx. 42 %) are conference papers. These publications often cover current trends and technological innovations and offer a practical perspective on the application of DTs in SMEs. The remaining 2 publications (approx. 5 %) are book chapters. These chapters offer a broader, contextual view and are often more theoretical, providing comprehensive overviews of DT applications in SMEs and the challenges they face.

The publication frequency shows an increase in recent years. *Figure 4* shows the development of published papers on the research topic from 2017.

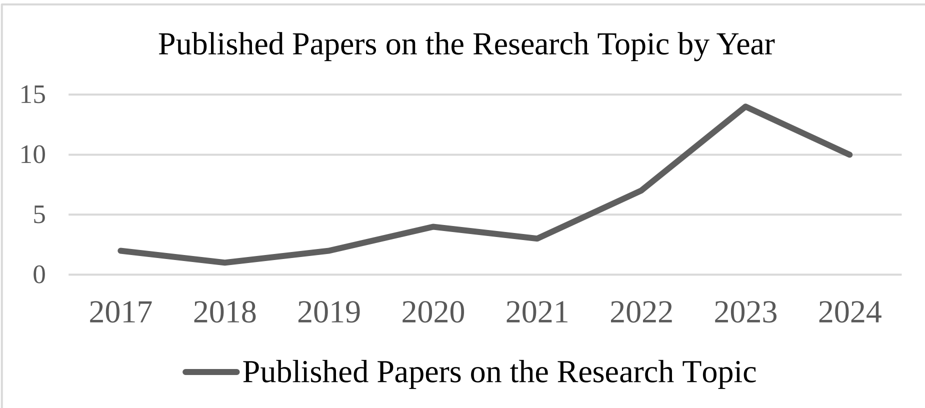

Figure 4 – Published Papers on the Research Topic by Year
Source: Own illustration, based on the research results (2024)

Most of the papers were published between 2022 and 2024, which shows the relevance of the research field. Before 2020, only 5 papers were published, while in 2020, four publications and in 2021, also three publications were submitted. In 2022 7 papers were published in relation to the topic under investigation rising to 14 publications in 2023. 10 publications in 2024 continue to demonstrate an increasing level of scientific activity in this field.

24 of the 43 papers analysed followed a qualitative research approach, while 7 papers took a quantitative approach, 8 papers a mixed approach and 4 a descriptive approach.

While many studies do not mention a specific geographical context, 11 focus on the implementation and impact of DTs in SMEs within a certain regional framework.

Asia is an important geographical area, particularly in the context of the manufacturing industry and energy-intensive processes. The study by Dutta et al. (2021) highlights the challenges and benefits of digitalising production facilities in Indian SMEs. The focus here is on increasing efficiency and introducing innovations to increase competitiveness in a cost-sensitive environment. Govindasamy et al. (2024) introduce a cost-effective und sustainable DT design for entertainment micro SMEs in India. South Korea is represented in studies such as Y. Park et al. (2020), which focuses on the introduction of a cloud-based DT manufacturing system designed for smart manufacturing in SMEs and K. T. Park et al. (2019), which presents a service-oriented platform for the dyeing and finishing industry, aiming to boost energy efficiency through Industrial Internet of Things integration in SMEs. The platform also utilizes analytical tools to manage energy consumption, reflecting sustainability goals, which is of great importance in a highly developed industrialised country like South Korea. The concept of "Lightweight Digital Twin as a Service" is introduced as a scalable digital transformation model for SMEs in China by Guo et al. (2023).

Europe is also playing an important role regarding the geographical context of the reviewed studies. Borghesi et al. (2021) focus on the general advantages and challenges for SMEs when implementing DTs and edge cloud solutions in an industrial context and highlights the support provided by the Horizon 2020 programme of the European Union, but remain at an overarching European level. The work of Jonek et al. (2023) emphasises that in countries with high labour costs, such as Germany, the integration of technologies such as DTs in combination with human-robot collaboration is of particular interest in order to increase productivity and cost efficiency. Grau et al. (2021) address the challenges and advantages of implementing DTs in process plants more generally, without focusing on specific regional or country-specific contexts, while providing application examples and discussions—such as the use of DTs in a biogas plant in Germany. De Felice et al. (2022) examine the implementation of DTs in Italian SMEs and show how this technology makes production more flexible and reduces costs. Løkke and Madsen (2023) analyse the role of DTs in energy and environmental technology to promote sustainability in SMEs, with a particular focus on Danish and European companies.

The Americas are represented with one study by Bi et al. (2023), who demonstrate how DTs are used in the USA to verify and validate sustainable production strategies across various sectors, including automotive applications, and how this technology supports SMEs in achieving their environmental sustainability goals.

Many studies have addressed an impact of DTs in industrial scenarios. Kawtar and Ahmed (2022) highlight applicability in Industry 4.0 contexts. Grau et al. (2021) describe an automated process for generating a digital twin in the process industry and Pacheco-Velazquez (2024) and Wicaksono et al. (2023) discuss the challenges and opportunities of DTs in the transport and logistics sector. However, most of the studies remain in a broad manufacturing context (Borghesi et al., 2021; Caccamo et al., 2022; De Felice et al., 2022; Dutta et al., 2021; Florescu & Barabas, 2022; García et al., 2024; Harrigan et al., 2023; Jonek et al., 2023; Kang & Kim, 2024; Y.-D. Kim et al., 2023; Kuts et al., 2022; Lima et al., 2019; Løkke & Madsen, 2023; Marra et al., 2024; Monek & Fischer, 2023; Mügge et al., 2024; Y. Park et al., 2020; Pires et al., 2020; Shevtshenko et al., 2020; Sommer et al., 2023; Ud Din & Paul, 2022; Uhlemann et al., 2017; Webb et al., 2024; Yang et al., 2023), while some focus on manufacturing in specific sectors, including aerospace (Rodič, 2017), agriculture (Bi et al., 2023; Zambrano et al., 2022), automotive (Bi et al., 2023; Rodič, 2017), automation (Landolfi et al., 2018), electromechanics (Dutta et al., 2021; Sit & Lee, 2023), entertainment (Govindasamy et al., 2024), food and beverage (Bär & Colombo, 2023), furniture (Krommes & Tomaschko, 2023), plastics and sheet metal processing (Zambrano et al., 2022), and textile (Guo et al., 2023; Huayanca Quispe et al., 2024; M. Kim et al., 2024; K. T. Park et al., 2019). Singhaphandu et al. (2024) focus their research on industrial manual assembly.

An important aspect of the synthesis is the distinction between the articles that directly analyse the impact of DTs on SME sustainability and the articles that indirectly identify the impact of DTs on SME sustainability as a secondary factor. Only two papers directly analyse the impact of DTs on the sustainability of SMEs: Bi et al. (2023) analyse the impact of how virtual verification and validation using a DT contributes to the sustainability of an SME, while Wicaksono et al. (2023) describe the development of an intelligent and trustworthy digital platform for the sustainable management of transport infrastructure using digital twins.

All other authors were able to identify the impact on the dimensions of sustainability as a secondary factor.

Figure 5 shows that all 43 studies identify economic impacts of DTs in SMEs, while only 29 address environmental aspects and 21 social aspects:

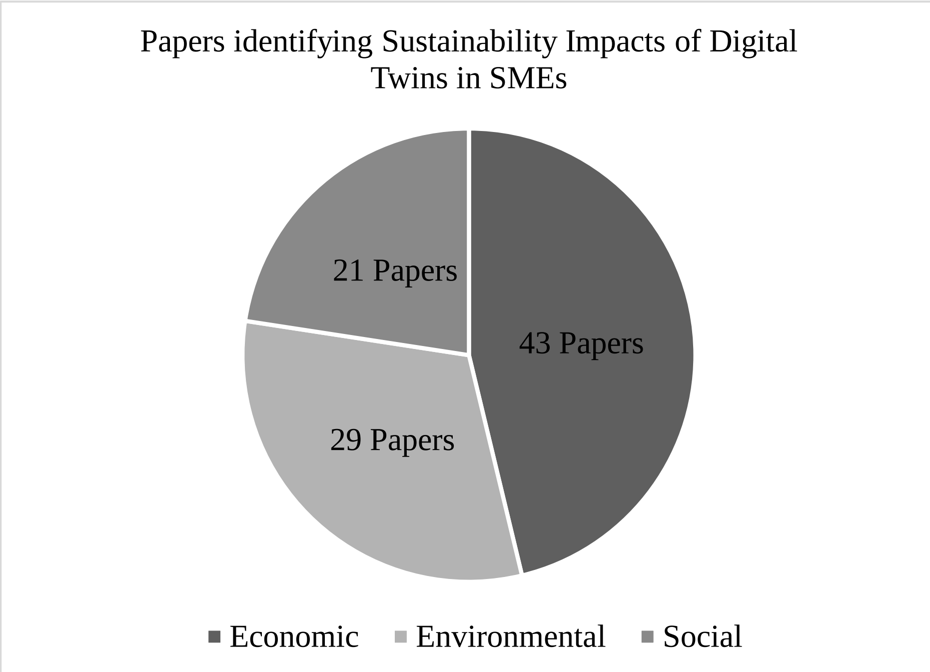

Figure 5 – Papers identifying Sustainability Impacts of Digital Twins in SMEs
Source: Own illustration, based on research results (2024)

Economic impact of Digital Twins on SMEs

All 43 analysed studies identify an impact of DTs on the economic sustainability of SMEs. Many of the investigated studies show that DTs can lead to significant productivity increases and optimised production processes in SMEs. DTs are increasingly recognised as key enablers of economic sustainability for SMEs, providing cost-effective solutions that improve efficiency, optimise resources, and support the development of new business models (Kaarlela et al., 2020; Lima et al., 2019; Marra et al., 2024; Mügge et al., 2024). Their ability to virtualise processes and equipment allows SMEs to simulate and optimise production operations, leading to reduced downtime, faster troubleshooting, and lower operational costs (Landolfi et al., 2018; Lima et al., 2019; Yang et al., 2023). DTs support real-time monitoring and data-driven decision-making, which enhances risk management, enables predictive maintenance, and improves supply chain coordination (Krommes & Tomaschko, 2023; Pires et al., 2020; Shevtshenko et al., 2020; Webb et al., 2024; Wicaksono et al., 2023). Several studies underline their contribution to increased productivity, operational flexibility, and resource allocation, particularly when integrated with MES, IoT, and cloud-based systems (Guo et al., 2023; Y. Park et al., 2020; Rodič, 2017; Uhlemann et al., 2017). In addition to direct savings, DTs offer indirect economic benefits by enabling more informed investment decisions, reducing programming and validation expenses, and facilitating faster responses to market changes (Deniša et al., 2023; Kuts et al., 2022; Pires et al., 2020). Their role in cost-effective training and education enhances workforce efficiency and supports competitiveness, particularly in dynamic, low-volume production contexts (Harrigan et al., 2023; Singhaphandu et al., 2024; Sit & Lee, 2023). DT-driven automation also strengthens SMEs' capacity for personalised manufacturing without the need for large capital investments (Monek & Fischer, 2023; Rodič, 2017). Applications in energy monitoring, logistics, and production planning demonstrate measurable returns, especially when aligned with predictive analytics and scenario-based optimisation (Kawtar & Ahmed, 2022; Pacheco-Velazquez et al., 2024; Webb et al., 2024). Despite these advantages, adoption challenges persist, including high implementation costs, limited IT expertise, and integration complexity—factors particularly relevant for resource-constrained SMEs (Caccamo et al., 2022; Sommer et al., 2023; Ud Din & Paul, 2022). Nevertheless, by improving ROI, enhancing agility, and reducing development costs through modular and AR-supported systems (Y.-D. Kim et al., 2023), DTs represent a transformative opportunity for SMEs to improve economic performance while navigating digital and market transitions.

Environmental impact of Digital Twins on SMEs

DTs play a pivotal role in advancing the ecological sustainability of SMEs by enabling both direct and indirect improvements in resource efficiency and environmental management. Through real-time monitoring and analysis of energy and material consumption, DTs help identify inefficiencies, optimize production systems, and reduce waste and emissions (M. Kim et al., 2024; Krommes & Tomaschko, 2023; Lima et al., 2019; Pires et al., 2020; Webb et al., 2024). Their capacity to track environmental indicators such as CO_2 emissions and waste output, provides SMEs with actionable insights for sustainable manufacturing and facilitates alignment with industry expectations for ecological responsibility (Løkke & Madsen, 2023; Mügge et al., 2024). By incorporating life cycle assessment (LCA) data and supporting circular economy principles, DTs allow for continuous monitoring of product and component conditions across their lifecycle, promoting more informed and sustainable resource decisions (Løkke & Madsen, 2023; Mügge et al., 2024; Zambrano et al., 2022). Additionally, DT-based simulations empower SMEs to virtually test alternative scenarios, evaluate their environmental impact, and make ecologically sound operational choices before implementation (Huayanca Quispe et al., 2024; Lima et al., 2019; Marra et al., 2024; Pires et al., 2020). Beyond operational optimization, DTs contribute to sustainability through predictive maintenance, which extends equipment lifespan, reduces the need for replacements, and reduces the overall consumption of resources (Landolfi et al., 2018; Pires et al., 2020; Wicaksono et al., 2023). Wicaksono et al. (2023) note that their integration into infrastructure and training systems also supports environmentally conscious practices that lead to more sustainable behaviour in the workplace and a better understanding of energy use among employees. In various high-impact sectors such as textiles, furniture, and manufacturing, DTs have been shown to lower material and energy demands while improving workflow efficiency and minimizing the ecological footprint of production processes (Borghesi et al., 2021; Kawtar & Ahmed, 2022; M. Kim et al., 2024; Yang et al., 2023). According to Rodič (2017) SMEs are able to transition toward more resource-aware and sustainable operations by leveraging sensor networks, Green IT, and intelligent data processing. Altogether, DTs represent an enabling technology that supports SMEs not only in achieving energy and material efficiency but also in meeting growing sustainability standards in a data-driven, cost-effective, and future-oriented way.

Social impact of Digital Twins on SMEs

Only a few of the studies pointed out a social impact of DTs.

A number of studies emphasize the contribution of DTs to occupational safety through real-time monitoring, predictive maintenance, and ergonomic task allocation, which help reduce physical strain and mitigate operational hazards (Jonek et al., 2023; Kuts et al., 2022; Mügge et al., 2024; Yang et al., 2023). These safety benefits extend to human-robot collaboration, where DTs facilitate hazard detection and promote adaptive task distribution, while also supporting regulatory compliance in resource-constrained settings (Jonek et al., 2023; Mügge et al., 2024; Yang et al., 2023). In terms of workforce development, DTs offer SMEs cost-effective and scalable training environments that promote employee upskilling and knowledge transfer through virtual simulations and learning ecosystems (Dutta et al., 2021; García et al., 2024; Harrigan et al., 2023; Kaarlela et al., 2020; Singhaphandu et al., 2024; Uhlemann et al., 2017). This is reinforced by intuitive interfaces such as augmented and virtual reality, which enhance accessibility for non-technical staff and reduce the learning curve for engaging with complex systems (Bär & Colombo, 2023; Guo et al., 2023; K. T. Park et al., 2019; Zambrano et al., 2022). By empowering employees to perform skilled tasks and engage in continuous learning, DTs not only close knowledge gaps but also increase job attractiveness and employee satisfaction (Bär & Colombo, 2023; Harrigan et al., 2023). DTs further strengthen social structures within and beyond the organization by improving transparency, supporting collaborative decision-making, and enabling knowledge sharing via shared data platforms (Pacheco-Velazquez et al., 2024; Pires et al., 2020; Shevtshenko et al., 2020; Wicaksono et al., 2023). Involving users in the development and application of DTs – particularly through accessible and comprehensible systems – also builds trust in digital technologies and fosters broader acceptance within the workforce (Bär & Colombo, 2023; Pires et al., 2020). Ultimately, the overall integration of digital technology into SMEs' operations contributes to socially sustainable practices by improving employee wellbeing, inclusion and long-term adaptability in a rapidly evolving technological landscape, even if certain digital skill challenges remain (Y.-D. Kim et al., 2023).

Analysis: Interpretation of the results in the context of existing literature

The SLR highlights a rapidly emerging, yet underdeveloped research area. It examines the ecological, economic, and social impacts of DTs on SMEs using 43 papers published between 2017 and 2024. While the scope of the studies predominantly centres on the economic dimension of sustainability, limited exploration of environmental and social aspects stress significant research gaps in this field. A summary of the identified impacts can be found in *Figure 6*.

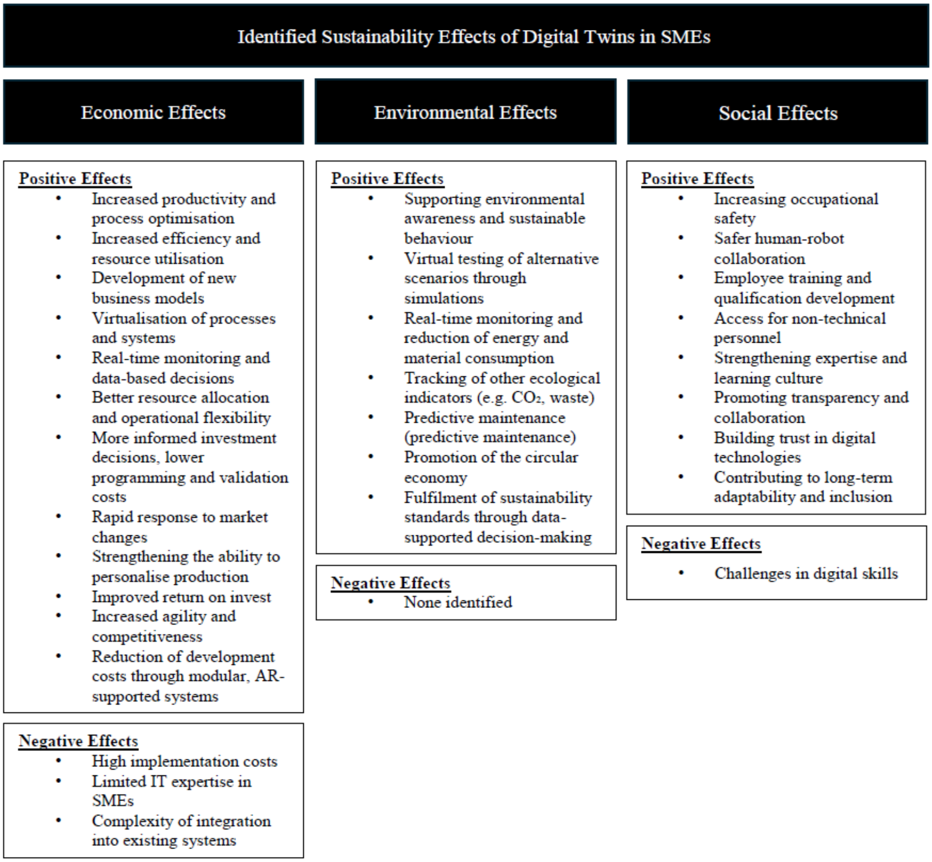

Figure 6 – Identified Sustainability Effects of Digital Twins in SMEs

Source: Own illustration, based on research results (2024)

Economic, Environmental, and Social Impacts of Digital Twins on SMEs

All 43 evaluated studies included in the analysis explicitly identify the economic benefits of DTs for SMEs.

DTs are recognised for their potential to increase operational efficiency, reduce costs and boost productivity. They enable predictive maintenance, minimise downtime and streamline resource allocation - outcomes critical for resource-constrained SMEs. Examples such as Huayanca Quispe et al. (2024) and Webb et al. (2024) showcase how real-time data-driven insights facilitate energy and resource optimization, leading to financial savings and enhanced return on investment. Additionally, DTs drive agility, enabling

SMEs to adapt swiftly to market demands, a trait increasingly vital in the modern industrial landscape.

Despite the promise, adoption barriers like high implementation costs and technical complexity remain persistent themes. Studies, including Sommer et al. (2023), highlight these challenges, emphasizing the need for targeted financial and technological support for SMEs.

The review found fewer studies (29 out of 43) addressing the environmental impact of DTs, though they universally point to positive outcomes. DTs enhance resource efficiency and waste reduction, align manufacturing with circular economy principles, and enable real-time energy consumption tracking. For instance, Mügge et al. (2024) and Webb et al. (2024) illustrate how DTs promote sustainability by reducing carbon footprints through optimized energy use. Similarly, Borghesi et al. (2021) and Zambrano et al. (2022) discuss how integrating DTs with LCA supports sustainable production by minimizing material waste.

A notable observation is the absence of any identified negative environmental impacts of DTs. This consistently positive assessment could reflect the still young state of the research field and a potential bias towards positive results.

The social dimension remains the least explored, with only 21 studies addressing the topic. DTs contribute to workplace safety, employee well-being, and skill development. For example, García et al. (2024) emphasize the use of DTs in structured employee training, while Mügge et al. (2024) discuss their role in predictive maintenance, which ensures safer work environments. Furthermore, DTs foster inclusivity by enabling non-technical staff to engage in digital transformation, as highlighted by Zambrano et al. (2022) and Y. Park et al. (2020).

Like the environmental domain, the review identifies no specific negative social impacts. This absence suggests either a lack of research focus on unintended consequences or genuinely negligible adverse effects, warranting further investigation.

Practical Recommendations for SMEs

A finding by Hansen et al. (2019) that is also discussed in the paper by Kaarlela et al. (2020) suggests, that many SMEs are already faced with the challenge of understanding the term Industry 4.0 in their own context and identifying concrete potential use cases for it. Based on the previously discussed findings, this section provides practical recommendations for SMEs to effectively utilise DTs in the pursuit of sustainability goals.

Pires et al. (2020) argue that the use of real applications and demonstrators is a suitable way to familiarise SMEs with new and innovative technologies and approaches such as the Digital Twin and to demonstrate the applicability, benefits and best practices of Digital Twin solutions.

SMEs can actively use digital twins to improve their sustainability performance by monitoring and optimising resource consumption, especially energy, in real time (Lima et al., 2019; Pires et al., 2020). Furthermore, digital twins enable predictive maintenance, which reduces downtimes, extends the service life of systems and thus allows resources to be used more efficiently (Landolfi et al., 2018; Pires et al., 2020; Wicaksono et al., 2023). By virtualising and simulating processes, SMEs can analyse different scenarios and identify more sustainable operating parameters (Lima et al., 2019; Pires et al., 2020). In addition, DTs offer valuable opportunities for circular economy strategies by improving transparency across the entire product lifecycle and enabling data-driven decisions, especially at the end of the lifecycle (Løkke & Madsen, 2023; Mügge et al., 2024).

It is advisable for SMEs to choose low-risk, scalable solutions as a starting point, such as lightweight digital twins offered as a service (LDTaaS) or pluggable IoT-based frameworks (Govindasamy et al., 2024; Guo et al., 2023; Kang & Kim, 2024). These options enable modular implementation without the need for significant upfront investment. In addition, SMEs should focus on specific, high-impact processes that directly affect their sustainability goals and apply cascading digital twins within these areas (Caccamo et al., 2022). Improving employees' digital skills is equally important; simulation-based training platforms can support this transition by fostering practical understanding and engagement for digital transformation (Uhlemann et al., 2017).

Furthermore, examples like Borghesi et al. (2021), Caccamo et al. (2022) and Deniša et al. (2023) show the need for collaboration with external experts, research organisations or other SMEs to facilitate knowledge sharing, cost reductions and implementation acceleration (Kawtar & Ahmed, 2022).

In addition, DTs offer valuable opportunities for circular economy strategies by improving transparency across the entire product lifecycle and enabling data-driven decisions, especially at the end of the lifecycle (Løkke & Madsen, 2023; Mügge et al., 2024).

Identified Patterns and Research Gaps

A significant pattern identified is the heavy emphasis on the economic benefits of DTs. All 43 studies discuss economic impacts, whereas only 29 and 21 studies address environmental and social impacts. However, this can be explained by the fact that almost all selected papers did not analyse the sustainability aspect as a main objective.

The limited number of 43 studies, many of which were conducted using qualitative methods, shows that the topic is still relatively new. The focus on DTs in sustainability for SMEs has emerged predominantly in recent years, with most papers published after 2020. This trend underscores the field's developmental stage and the need for longitudinal, empirical research to substantiate current findings. Notably, only two studies (Bi et al., 2023; Wicaksono et al., 2023) directly examine the sustainability impact of DTs in SMEs, while the remaining literature explores sustainability as a secondary or incidental factor. This highlights a critical gap: the lack of focused, empirical investigations into DTs' role in advancing sustainability across all three dimensions in SMEs.

Contradictory findings are minimal within the reviewed literature, likely due to the field's emerging status and the dominance of qualitative studies. Most sources align in presenting DTs as enablers of economic, environmental, and social improvements. However, few challenges such as high implementation costs and technical complexity, mentioned by studies like Krommes and Tomaschko (2023), contrast with the generally optimistic narratives of DT benefits. These challenges may deter SMEs with limited resources, underscoring the need for scalable, cost-effective solutions tailored to SMEs' capacities.

The studies do not report direct or significant negative impacts on the environmental or social sustainability dimension. This absence may either be due to an oversight in previous research or a genuine lack of harmful effects in the early stages of implementation. Given the increasing reliance on DTs, future research needs to directly and critically examine potential unintended consequences, such as resource-intensive initial implementations or workforce disruption. The fragmented treatment of the TBL across studies indicates a lack of holistic perspectives. Few studies attempt to consider all dimensions, limiting comprehensive insights into how DTs can simultaneously address all aspects of sustainability.

Further, the geographical focus is uneven, with significant representation from Asia and Europe but limited insights from other regions like Africa or the Americas. Similarly, the industrial focus is skewed toward manufacturing, with limited exploration of DT applications e.g. in service-oriented SMEs.

Discussion and Conclusion

This SLR aimed to answer the central research question:

> '*What is the current state of literature regarding the economic, environmental, and social impact of Digital Twins on SMEs?*'.

By synthesizing insights from 43 studies published between 2017 and 2024, the review provides an essential overview of the field and fulfils its objective of offering a structured understanding of the role of DTs in promoting sustainability in SMEs.

The findings suggest that the research on the sustainability dimensions of DTs on SMEs is emerging but remains fragmented and underdeveloped. The economic dimension dominates the discourse, with all 43 studies identifying significant positive effects. DTs are recognized as transformative tools that enable SMEs to reduce operational costs, optimize production processes, and increase productivity. They facilitate predictive maintenance, real-time decision-making, and resource efficiency, helping SMEs overcome some of their inherent limitations, such as resource constraints and operational inefficiencies.

In contrast, the environmental and social impacts of DTs are less frequently addressed. Only 20 of the reviewed studies explore environmental aspects, focusing on positive outcomes such as energy efficiency, waste reduction, and alignment with circular economy principles. DTs are shown to support life-cycle assessments and promote sustainable production, although there is a noticeable absence of studies investigating potential negative environmental consequences.

The social impact is the least examined, with only 18 studies touching on this aspect. Research highlights contributions to workplace safety, employee training, and inclusivity, emphasizing the potential of DTs to foster skill development and ergonomic task distribution. However, the lack of studies explicitly addressing social sustainability as a primary focus represents a significant gap.

In conclusion, this review achieved its objective of providing a structured overview of the literature on the sustainability impacts of DTs for SMEs. By employing the PRISMA and SALSA frameworks, the review systematically identified, screened, and analysed relevant studies. It demonstrated that DTs hold substantial promise for SMEs in achieving sustainability goals but also exposed critical gaps in the literature, particularly in longitudinal studies and integrative approaches that address the TBL. However, it is important to highlight that the results of the literature review are only seen and interpreted in the context of the outlined significant research gaps.

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