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Sopron, 2025. november 6.

6 November 2025, Sopron

FEJLŐDÉSI PÁLYÁK ÉS ÚJ TÖRÉSVONALAK A FENNTARTHATÓSÁGI ÁTMENET IDŐSZAKÁBAN

DEVELOPMENT TRAJECTORIES AND NEW DIVIDES IN TIMES OF SUSTAINABILITY TRANSITIONS

Szerkesztők / Editors:
RESPERGER Richárd, SZÉLES Zsuzsanna, TÓTH Balázs István

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Digital Twins in Sustainable Supply Chain Management: An Exploratory Cross-Case Analysis

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Abstract:
Digital Twins (DTs) are increasingly recognized as a promising approach for integrating sustainability into supply chain management by enabling virtual replication, scenario testing, and optimisation of complex operational systems. However, systematic understanding on how DTs are implemented in practice to achieve sustainability goals remains limited. This paper addresses this gap through an exploratory, cross-case examination of five documented DT implementations in the supply chain across various industries. Drawing on secondary data from peer-reviewed literature, industry reports, and corporate documentation, the analysis identified patterns in sustainability contributions, technological requirements, and organisational conditions across diverse applications. Three principal findings emerge. DTs currently offer sustainability benefits primarily through improvements in operational efficiency that have a positive impact on the environment, rather than through targeted environmental measures. Energy consumption and emissions are the most measured outcomes, with measurement methods and verification standards varying significantly depending on implementation. Improvements in transparency are largely limited to the boundaries of the organisation and do not extend across multi-tier supply chains. Key success factors include technological infrastructure for continuous data collection, simulation capabilities, and the organisational capacity for system integration with documented applications found primarily in large, resource-rich companies in technologically advanced industries. These patterns suggest that the contribution of DTs to supply chain sustainability remains limited and context dependent. To realise greater potential, it is necessary to move beyond isolated efficiency applications and pursue integrated approaches that ensure transparency and coordination across organisational boundaries.

Keywords: digital twins (DTs), sustainability, supply chains, sustainable supply chain management (SSCM), green logistics
JEL Codes: L23, L91, M11, O33, Q56

1. Introduction

Sustainable Supply Chain Management (SSCM) has become a critical concern as firms face pressure from regulatory requirements, stakeholder expectations, and environmental needs to reduce negative sustainability impacts across production and logistics, requiring improved visibility and optimization throughout complex supply networks. The European Green Deal and recent evolving regulatory developments, such as the European Union's Corporate Sustainability Due Diligence Directive (CSDDD) as well as the Corporate Sustainability Reporting Directive (CSRD) illustrate the growing institutional demand for verified sustainability data across the entire supply chain (Directive (EU) 2024/1760, 2024).

Achieving these goals will require not only operational changes, but also improved capabilities for monitoring, measuring, and optimising environmental impacts across geographically dispersed and organisationally fragmented supply chains.

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Digital Twin (DT) technology has emerged as a promising tool in this context (Zhang et al., 2021). By simulating and monitoring operations in near real-time, DTs can identify inefficiencies, reduce waste, and optimize resource use. However, the practical application of DTs for SSCM is still at the development stage. While digital technologies are widely discussed as enablers of sustainable supply chains, empirical evidence on their concrete implementation mechanisms lacks detailed insights. It remains unclear how organisations can effectively use DT for sustainability, and the key factors and barriers to success are not yet well understood. There is a lack of longitudinal studies, industry-specific implementation frameworks, and empirical assessments of the environmental impact of DT infrastructure across its entire lifecycle (Kober et al., 2025; Seegrün et al., 2023). Furthermore, there are few studies that compare success factors across sectors or regions. This article addresses these gaps by providing a cross-sector comparative analysis of DT use cases, highlighting both enabling factors and barriers, and assessing their alignment with sustainability goals.

This article fills these gaps through an exploratory analysis of five documented DT implementations from logistics, manufacturing and warehousing contexts. Based on secondary data from academic publications, industry reports and corporate documentation, the analysis examines how these implementations contribute to sustainability goals, which technological and organisational conditions that enable their use, and what obstacles limit their effectiveness. Rather than offering normative frameworks or causal statements, the study identifies patterns, shared characteristics and tensions between the cases to support research understanding and practical decision-making.

Accordingly, the research question underlying this work is:
How are DTs used in practice to enhance supply chain sustainability, and what are the key enablers and barriers influencing their successful implementation?

The structure of the paper is as follows: Chapter 2 provides an overview of the conceptual foundations related to DTs and sustainable supply chains. Chapter 3 outlines the methodological approach of the paper, followed by Chapter 4, which presents a cross-case analysis of five implementations. Chapter 5 discusses findings and their broader implications and limitations. Chapter 6 concludes the paper with a summary and outlook on future research.

Figure 1: Structure of the Paper
Source: Own illustration (2025)

2. Research Background

DTs have emerged as a promising approach for integrating sustainability into supply chain management. The concept introduced by Michael Grieves in 2003 (Grieves & Vickers, 2017) refers to virtual representations of physical systems that are continuously linked to its physical counterpart through continuous data exchange (Kritzinger et al., 2018; Negri et al., 2017).

Unlike traditional simulations or static digital models based on historical data, DTs use near real-time information to mirror current conditions and enable organisations to test scenarios, anticipate problems, and optimise operations without disrupting actual processes (Jones et al., 2020; Negri et al., 2017).

This capability has led to growing interest in applying DTs to address sustainability challenges in supply chains, particularly for monitoring emissions, optimising resource use, and improving transparency (Kamble et al., 2022a).

The potential relevance of DTs for sustainability is particularly evident considering the ongoing challenges in managing sustainable supply chains.

The triple bottom line concept by Elkington (2004), which integrates economic, environmental, and social dimensions requires firms to manage not only cost, quality, and speed, but also environmental responsibilities such as emissions reduction and resource efficiency, as well as social issues like working conditions and human rights in their supply chains (Seuring & Müller, 2008). SSCM is therefore defined as managing material, information, and financial flows while considering stakeholder needs and sustainability in all three areas (Seuring & Müller, 2008). However, implementing these principles in global supply chains poses major challenges. The complexity of globally distributed supplier networks often limits transparency (Tachizawa & Wong, 2014) beyond Tier 1 suppliers, making it hard to monitor and enforce sustainability standards across all levels (Tachizawa & Wong, 2014).

Another challenge is the tension between economic and sustainability goals. Initiatives such as using low-emission transport or investing in environmentally friendly supplier practices often increase costs initially (Hassini et al., 2012). These challenges limit the ability of organisations to identify improvement opportunities, demonstrate progress, and make informed decisions about sustainability investments.

Despite widespread recognition of the potential of digital technologies for sustainable supply chains, existing research lacks detailed insights into their implementation in practice. It remains unclear how organisations can effectively use DT for sustainability, and the key factors and barriers to success are not yet well understood. There is a lack of longitudinal studies, industry-specific implementation frameworks, and empirical assessments of the environmental impact of DT infrastructure across its entire lifecycle (Kober et al., 2025; Seegrün et al., 2023).

3. Methodological Approach

This study uses a qualitative, exploratory approach to examine how DTs are currently used to support sustainability goals in supply chain management. Due to the emerging and fragmented state of research on DT implementations, an exploratory design is appropriate to identify recurring patterns, technological characteristics, and practical challenges across different sectors and application contexts. The analysis synthesises insights from documented implementations reported in peer-reviewed scientific publications, reports from research institutions and publicly available corporate documentation. These secondary sources were selected because they provide detailed descriptions of DT implementations in practice including descriptions of technological foundations, organisational conditions, and sustainability related outcomes. The focus on secondary data is justified by the exploratory nature of this study and the need to capture a broad range of implementation contexts that would be difficult to access through primary data collection within the scope of a conference paper.

Implementations were selected according to three criteria to ensure breadth and analytical relevance. First, the sample reflects sectoral diversity, including examples from automotive, electronics and logistics supply chains. Second, implementations at different stages of maturity were included, from pilot projects and research initiatives to fully operational, integrated solutions. This variation enables the identification of patterns across different levels of technological sophistication. Third, only implementations for which publicly accessible sources reported measurable sustainability results, such as reductions in CO_2 emissions, energy consumption or material waste, were considered. Applying these criteria resulted in a sample of ten documented implementations referenced in the scientific and industry literature. From these, five implementations met the level of detail and documentation required for structured cross-case analysis.

The analysis followed a structured approach based on established methods for synthesising qualitative data from multiple sources (Eisenhardt, 1989; Yin, 2018). Each implementation was examined with respect to the purpose and scope of DT implementation, the technological and data foundations described, the sustainability outcomes reported, and the organisational or contextual factors identified as enablers or barriers. This dimensional analysis was applied consistently across all implementations to support the identification of overlapping topics. The synthesis focused on convergent patterns regarding technological requirements, organisational preconditions, and sustainability contributions, as well as recurring challenges in implementation. While this approach does not permit causal claims or statistical generalisation, it provides a structured basis for identifying common themes and generating insights relevant to research and practice.

4. Digital Twins and Sustainability in Supply Chains

In modern supply chains, digitalisation and sustainability are increasingly becoming complementary drivers that reinforce each other. Companies are facing a double transformation, on a digitalisation and a sustainability level. Advancing digitalisation offers new tools to achieve sustainability goals in the supply chain more effectively (Kamble et al., 2022b). Digital technologies such as IoT, big data analytics, blockchain and especially DTs make it possible to make supply chains more transparent, efficient and responsive, which brings immediate sustainability benefits (Kamble et al., 2022b; Khan et al., 2025).

This chapter examines five documented DT implementations across logistics, manufacturing and warehousing contexts. The analysis focuses on how these implementations address sustainability objectives and what organisational and technological conditions enable their success.

Table 1 provides an overview of the cases, their application contexts, and reported sustainability impacts.

Table 1: Case Overview[2]

Implementation	Sector	Application Focus	Primary Sustainability Impact	Source
DHL Supply Chain	Logistics	Network optimisation, modal shift analysis	CO_2 reduction through route and mode optimisation	Dohrmann et al. (2019)
Pusan Newport Terminal	Port operations	Process optimisation, incident simulation	62-174 tons CO_2 savings (Scenario based)	Eom et al. (2023)
BMW iFactory	Automotive production	Production planning, facility layout	30% planning acceleration, reduced material waste	BMW Group (2022)
LG Electronics Changwon	Electronics manufacturing	Production optimisation	30% energy reduction, 70% quality improvement	Kaplan (2023)
Procter & Gamble Guangzhou (P&G)	Warehousing	Inventory and process management	30% inventory reduction, energy savings	Kaplan (2023)

Source: Own research, 2025

[2] Note: Sustainability impacts reflect outcomes reported in available documentation. Measurement methodologies and timeframes vary across cases.

The implementations analysed cover various supply chain functions and DT maturity levels.

DHL Supply Chain has developed a comprehensive network optimisation tool that enables scenario-based analysis of transport modes and warehouse locations (Dohrmann et al., 2019). Pusan Newport Terminal has deployed a port operation twin for near real-time process optimisation (Eom et al., 2023). BMW's iFactory initiative has set up factory twins at 31 production sites for planning and layout optimisation (BMW Group, 2022). LG Electronics implemented a manufacturing twin at its Changwon plant that continuously integrates operational data (Kaplan, 2023). Procter and Gamble created a warehouse twin for inventory and process management at its Guangzhou plant (Kaplan, 2023). Although these implementations vary in scope and technical complexity, a cross-case analysis reveals several consistent patterns in terms of their contributions to sustainability, their technological foundations, and their organisational requirements.

In addition to the five implementations examined in detail, several other examples illustrate the application of DTs in specific sustainability contexts. Schneider Electric's plant in Le Vaudreuil achieved energy savings and a 17% reduction in material waste (Sahu, 2022). The Fraunhofer EcoTwin research project is developing lifecycle-oriented DTs for applications in the circular economy, using an industrial car wash as a demonstration case (Fraunhofer-Institut für Entwurfstechnik Mechatronik, 2025). Bosch's washing machine leasing project uses DTs for predictive maintenance in product-as-a-service models (Robert Bosch Manufacturing Solutions GmbH, 2025). Although these examples provide valuable insights, they cannot be systematically included in a cross-case analysis due to their varying degrees of documentation.

4.1. Sustainability outcomes and Performance Impacts

The most frequently reported sustainability benefits relate to resource efficiency and emission reduction. Energy consumption has become a priority in manufacturing and warehousing applications. LG Electronics achieved a 30% reduction in energy consumption through continuous process optimisation (Kaplan, 2023), while Schneider Electric recorded energy savings of 25% through improved factory management (Sahu, 2022). Implementations at P&G and DHL distribution centres resulted in a 15-25% reduction in energy consumption for lighting, air conditioning, and operations (Dohrmann et al., 2019; Kaplan, 2023).

DHL's distribution centres in particular reported up to 25% lower energy consumption for lighting and air conditioning, 30% faster picking processes, and an overall 20% reduction in CO_2 emissions in the warehouse (Dohrmann et al., 2019). Transport and logistics applications focused on reducing emissions through route optimisation and transportation shift , with the Pusan Termina documenting potential CO_2 savings of 62 to 174 tons in specific operating scenarios (Eom et al., 2023).

Beyond direct environmental metrics, several implementations reported efficiency gains with indirect sustainability impacts. Accelerating production planning at BMW by 30% reduced material waste and start-up inefficiencies (BMW Group, 2022, 2023). P&G achieved cost savings and a 30% reduction in inventory, which reduced storage requirements and the associated consumption of resources (Kaplan, 2023).

These results suggest that DTs often achieve sustainability benefits as a side effect of operational optimisation rather than through targeted environmental measures. It is important to note, that the reported results vary in terms of their methodological rigor. Some implementations provide scenario-based forecasts rather than measured results (Eom et al., 2023), while others report aggregate benefits without specifying measurement methods or baseline comparisons (Dohrmann et al., 2019; Kaplan, 2023). These differences make it difficult to evaluate across cases and highlights the need for more standardised sustainability evaluation frameworks.

4.2. Technological and Data Foundations

Successful implementations share common technological requirements despite varying in size and complexity. All cases are based on continuous data collection from operating systems, although the integration approaches differ. Manufacturing applications at LG Electronics and BMW use production system data that is updated at intervals ranging from seconds to minutes (BMW Group, 2022, 2023; Kaplan, 2023). Logistics and warehouse implementations integrate inventory management systems, transport data, and sensors in the facilities (Dohrmann et al., 2019; Kaplan, 2023). The case of the terminal in Pusan shows integration with external data sources such as shipping schedules and weather forecasts (Eom et al., 2023).

Simulation and optimisation functions form the central functional level of all implementations. DHL's network twin enables scenario testing for strategic decisions on location selection and means of transport (Dohrmann et al., 2019). BMW and LG Electronics use simulations for production planning and quality forecasting (BMW Group, 2022, 2023; Kaplan, 2023). Warehouse twins at P&G and DHL model process flows to identify bottlenecks and virtually test operational changes (Dohrmann et al., 2019; Kaplan, 2023). These functions are based on an analytical infrastructure, including cloud computing for processing, algorithms for optimisation, and visualisation tools for decision support. However, the detailed technical specifications remain proprietary, which limits comparative analysis of architectural decisions and their impact on performance.

4.3. Organisational Conditions and Implementation Challenges

The cross-case analysis identifies several organisational factors that influence the success of implementation. Management commitment appears to be crucial, especially in large-scale initiatives such as BMW's iFactory, which involves 31 plants and requires significant capital investment (BMW Group, 2022, 2023). Qualified personnel capable of managing data integration, model development, and interpretation is another common requirement. Implementations that cross organisational boundaries or span multiple locations present additional coordination challenges (BMW Group, 2022, 2023; Dohrmann et al., 2019).

Integration with existing systems poses a persistent obstacle. When implementing in warehouses, difficulties arise in connecting DTs to warehouse management systems and enterprise resource planning platforms (Dohrmann et al., 2019; Kaplan, 2023). Manufacturing applications must be connected to production control systems, quality management tools, and supply chain planning software (BMW Group, 2022, 2023; Kaplan, 2023; Sahu, 2022). Problems with data standardisation and interoperability exacerbate these challenges, especially in implementations that are intended to involve multiple suppliers or partners (Eom et al., 2023). The Fraunhofer EcoTwin project explicitly addresses this barrier by developing standardised data models for lifecycle assessment (Fraunhofer-Institut für Entwurfstechnik Mechatronik, 2025; Robert Bosch Manufacturing Solutions GmbH, 2025).

Investment requirements and resource constraints limit adoption, especially among smaller companies. While large manufacturers such as BMW and Schneider Electric can justify significant investments in infrastructure (BMW Group, 2022, 2023; Sahu, 2022), the implementations analysed provide limited information about cost-benefit considerations or payback periods. This gap makes it difficult to assess the feasibility of DTs in different organisational contexts and raises questions about scalability beyond resource-intensive pilot projects. Furthermore, most documented implementations originate from large, technologically advanced companies in developed economies, suggesting that adoption patterns may not reflect the general capabilities of the industry or applicability in different operational contexts.

5. Discussion

This chapter provides a synthesis of the findings of the cross-case analysis and critically reflects on their implications for understanding the contribution of DTs to supply chain sustainability. The discussion links the implementation patterns observed in the five cases to broader questions about technological enablers, organisational requirements, and the tensions associated with using digital infrastructure for environmental goals.

5.1. Supply Chain Sustainability Challenges

The analysis shows how DTs address the major challenges in SSCM:

On the transparency limitations, the cases demonstrate that DTs primarily provide enhanced transparency within organisational boundaries rather than across the entire supply chain. BMW's factory twins offer comprehensive transparency across 31 production sites, while LG's manufacturing twin enables continuous monitoring of production processes (BMW Group, 2023, 2023; Kaplan, 2023). However, none of the analysed implementations achieve real transparency across multiple levels of the supply chain. DHL's network optimisation tool and Pusan Terminal's port management system improve transparency in specific areas of operations, but do not extend to upstream suppliers and downstream distribution partners. This suggests that DTs currently serve as tools for transparency within an organisation rather than for end-to-end supply chain transparency.

The challenge of measurement is receiving greater attention in all cases. All implementations generate quantified sustainability metrics, but with varying degrees of accuracy. Energy consumption is the most consistently measured outcome, with LG reporting a reduction in 30% and Schneider Electric a decrease of 25% (Kaplan, 2023; Sahu, 2022). In comparison, the quantification of emission appears problematic, as Pusan Terminal provides scenario-based forecasts rather than verified reductions (Eom et al., 2023). This discrepancy highlights an important difference: DTs simplify measurement by generating data, but translating operational data into standardised sustainability metrics requires additional analytical frameworks and validation processes that are not always apparent in the available documentation.

In the tension between efficiency and sustainability, the case studies show that DTs generally bring environmental benefits as by-product of operational optimisation. The acceleration of production planning at BMW by 30% reduces material waste through fewer errors and shorter start-up times (BMW Group, 2022, 2023). The inventory reduction of 30% at P&G reduces storage space requirements and the associated energy consumption (Kaplan, 2023). This suggests an alignment between efficiency and sustainability in certain contexts but raises questions about the effectiveness of DTs when environmental goals conflict with operational metrics. None of the cases analysed explicitly address scenarios in which improvements in sustainability require compromises in efficiency, which limits the understanding of the benefits of DTs in such situations.

5.2. Technological and Organisational Requirements

The cross-case analysis identified several requirements for the successful implementation of DTs in the context of sustainability. At the technological level, continuous data collection from operational systems forms a universal basis, even If the specific architectures vary considerably. Implementations in manufacturing use existing production control systems, while logistics applications integrate multiple data sources, including external information such as weather forecasts and shipping schedules.

This diversity complicates technology transfer between different contexts and explains why standardisation initiatives such as the EcoTwin project of the Fraunhofer Institute and the registration platform of Bosch have emerged (Fraunhofer-Institut für Entwurfstechnik Mechatronik, 2025; Robert Bosch Manufacturing Solutions GmbH, 2025). Analytical capabilities, especially simulation and optimisation functions, represent the second technological requirement. The cases show that value creation depends on transforming data into decision support rather than simply collecting information. The DHL scenario tests for traffic shifts and BMW's layout optimisation illustrates this principle (BMW Group, 2022, 2023; Dohrmann et al., 2019). However, the proprietorial nature of analytical algorithms and optimisation logic limits the assessment of how different technical approaches affect sustainability outcomes. This lack of transparency makes it difficult to distinguish superior technological decisions from organisational or contextual advantages.

Organisational requirements focus on management commitment and integration capabilities. The resource effort observed in the company-wide rollout at BMW across 31 plants with 15,000 users is in strong contrast to the more focused applications at individual sites (BMW Group, 2022, 2023). The importance of managerial commitment reflected in these cases is consistent with recent research on sustainable leadership, which shows that long-term oriented and ethically grounded leadership approaches are essential for embedding sustainability-related innovation within organisations (Seese & Dióssi, 2024).

This difference suggests that the scope of implementation has a significant impact on organisational requirements, although the available documentation provides only limited insight into the coordination mechanisms, governance structures, or change management approaches that enable large-scale rollout. The integration challenges identified in the warehouse and manufacturing context reflect friction between DT systems and existing enterprise software and point to organisational rather than purely technical barriers (Dohrmann et al., 2019; Kaplan, 2023).

The focus on documented implementations in large, technologically advanced companies raises important questions about the accessibility of DTs. None of the analysed cases come from small or medium-sized industries. This pattern may indicate actual barriers to adoption or simply reflect a bias in the documentation, but it limits understanding of implementation requirements in different organisational environments. Whether the factors identified in these cases are transferable to resource-constrained environments or different industry structures remains an empirical question that requires more detailed investigations.

5.3. Tensions and Ambiguities

When examining DT applications from a critical sustainability perspective, several tensions come to light. The ecological footprint of the digital infrastructure itself receives minimal attention in the available case studies. Although the implementations report energy savings through optimised processes, none of them systematically consider the energy consumption of servers, data centres, and the computing infrastructure that support DT functionality. The 25% energy savings achieved by Schneider Electric do not provide comparable metrics for the energy consumptions of the DT system itself (Sahu, 2022). This asymmetry makes it difficult to assess the net environmental impact and suggests that the reported sustainability benefits may overstate the actual improvements if infrastructure costs are not considered.

The temporal dimension of sustainability outcomes also needs to be carefully examined. Many of the reported benefits reflect forecasts, scenario analyses, or short-term measurements rather than sustained, verified improvements over longer periods of time. The documented CO_2 savings at the Pusan Terminal come from the simulation of specific incidents rather than operational implementation (Eom et al., 2023). The acceleration in planning reported by BMW occurred in the early phase of implementation, with uncertainty regarding long-term performance and whether efficiency gains would persist as the system matured (BMW Group, 2022, 2023). This pattern raises the question of whether early pilot successes lead to lasting sustainability contributions.

Another critical tension is scalability. While BMW demonstrates the use of DTs in multiple facilities, most cases describe isolated applications within individual operational contexts. The challenges of scaling DTs across organisational boundaries, supplier networks, or multi-tier supply chains are only addressed to a limited extent in the available documentation. This gap is significant because many sustainability challenges in supply chains, especially transparency and coordination across different levels, require precisely the kind of cross-boundary capabilities that current implementations appear to lack. It cannot be determined from the available evidence, whether technical limitations, organisational barriers, or commercial sensitivities explain this pattern, but the implications for the contribution of DTs to systemic supply chain sustainability are significant.

5.4. Limitations and Implications for Future Research

There are several limitations that restrict the conclusions that can be drawn from this analysis. Since secondary data from published sources was used, the details of implementation, measurement methods, and challenges are only partially documented. Information asymmetry is particularly pronounced regarding technical specifications that are protected by copyright, as well as regarding failures or abandoned initiatives, which are systematically underrepresented in public documentation. Although the five cases analysed differ in terms of their scope of application, they share common characteristics that limit their generalisability: All involve large resource-rich companies in developed economies with significant technological capabilities. Sustainability outcomes in different organisational contexts, particularly in small and medium-sized enterprises or in less digitised industries, may vary significantly.

The exploratory nature of this study excludes causal statements about the effectiveness of DTs. The observed improvements in sustainability cannot be attributed solely to the use of DTs, but also to other initiatives, broader efficiency programs, or external factors. Furthermore, due to the lack of control cases, it is not possible to determine whether similar results could be achieved with alternative approaches. The cross-case synthesis identifies patterns and commonalities but cannot determine whether these are necessary conditions for success or only characteristics of the specific analysed implementations.

Future research should address these limitations in various ways. Longitudinal studies that track the implementation of DTs over longer periods of time would clarify whether the reported benefits are only temporary gains or sustainable improvements. Comparative studies that also include failed or abandoned implementations would provide a more balanced understanding of success factors and barriers. The collection of primary data through access to organisations would allow for more detailed examination of technical architectures, organisational processes, and measurement methods. Research in different organisational contexts, particularly in small and medium-sized enterprises and developing countries would test, whether the identified patterns are transferable to different resource environments.

Life cycle analyses that consider the environmental costs of digital infrastructure alongside operational benefits would enable a more comprehensive assessment of the net impact on sustainability.

6. Conclusion

This paper examined DT applications in the field of supply chain sustainability through a cross-case analysis of five documented implementations throughout the supply chain. By synthesising secondary data from industry reports and scientific patterns in how DTs address sustainability challenges, the conditions that enable their success, and where significant gaps remain.

Three key insights can be derived from the analysis. DTs currently improve sustainability primarily through increases in operational efficiency that have positive side effects for the environment, rather than through targeted environmental measures. Further, energy consumption and emissions reduction are the most measured outcomes, although measurement methods and verification standards vary significantly depending on the implementation. Also, improvements in transparency remain largely confined to organisational boundaries and do not extend to multi-tier supply chains, limiting the contribution of DTs to the systemic visibility challenges characteristic of SSCM.

Successful implementation depends on infrastructure for continuous data collection, simulation capabilities for scenario testing, and organisational capacity for system integration, with documented applications found primarily in large, resource-rich companies in technologically advanced industries.

These findings have several implications for practice and research. Organisations considering the use of DTs for sustainability reasons should be aware that the benefits are the greatest when environmental goals are aligned with operational efficiency goals, particularly in energy-intensive manufacturing and warehousing contexts. Investments in standardised measurement frameworks and lifecycle assessment methods would enable a more rigorous assessment of net environmental impacts, considering the infrastructure costs of the digital systems themselves. Key areas for research include longitudinal studies that track sustainable outcomes beyond initial adoption, comparative analyses that incorporate implementation failures and successes, and investigations of adoption patterns in resource-constrained organisational environments. The exploratory nature of this study and its reliance on secondary data from a limited sample of implementations limit its generalisability and point to the need for primary data collection and broader sampling across different industry contexts.

DTs offer promising but only partial contributions to the transformation of sustainability in the supply chain. To realise their potential, it is necessary to move beyond isolated efficiency applications and pursue integrated approaches that address the challenges of transparency, measurement, and coordination across organisational boundaries. Whether such systemic applications can overcome the current, technical, organisational, and economic barriers remains an open question that requires further empirical investigation.

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