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Nexus Between Digital Twin, Green Supply Chain Management, and Environmental Performance: Decoding Conceptual Roots

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Abstract

For improving operational and environmental performance, the confluence of sustainability and digital innovation has propelled businesses to explore novel approaches. This study examines the role of digital twin (DT) technology in enhancing environmental performance (EP) through Green Supply Chain Management (GSCM) practices. While prior research has examined GSCM and EP, limited studies have investigated the integrated relationship between digital twin technology, GSCM practices, and environmental performance. To address this gap, the current study develops a conceptual model based on a systematic literature review of prior research. The study employs a qualitative research approach, making use of secondary data collected from academic databases such as Web of Science, Scopus, and Google Scholar. Grounded Theory and Conceptual Framework Analysis (CFA) are adopted to identify key constructs and investigate their relationship. The findings suggest that DT enhances supply chain visibility, instantaneous tracking, and forecast-based decision-making, supporting the execution of GSCM approaches such as reverse logistics, eco-design, and green purchasing. Furthermore, the integration of DT enhances environmental outcomes through maximizing resource productivity by mitigating emissions. The study proposes a conceptual model that links DT, GSCM, and environmental performance. It also provides practical implications for businesses to achieve environmental sustainability through digital transformation. Future research should emphasise empirical analysis of the proposed framework in various industries.

Keywords: Digital Twin, Environmental Performance, Green Supply Chain Management (GSCM), Sustainability.

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Introduction

The increasing ecological issues and sustainability pressures have encouraged businesses to incorporate advanced technologies and green supply chain approaches. For the sake of instilling a spirit of sustainability and for managing environment-oriented industrial operations, it has been observed that Digital Twin technology is pivotal in the contemporary era of automation. DT technology also facilitates simulation, real-time tracking, and refinement in industrial processes by creating a virtual model of a physical (tangible) system (Grieves & Vickers, 2016; Tao et al., 2018). Digital twin technology enhances predictive decision-making along with operational visibility in supply chain systems by combining technologies such as IoT, data analytics, and artificial intelligence (Kritzinger et al., 2018).

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Simultaneously, GSCM has increasing attention as businesses seek to incorporate ecological aspects into supply chain operations such as logistics, production, and procurement (Srivastava, 2007; Zhu & Sarkis, 2004).

GSCM approaches, including green purchasing, reverse logistics, and eco-design, contribute to minimising ecological impacts and enhancing resource productivity (Çankaya & Sezen, 2018). Despite the increasing interest in sustainability and digitalisation, limited studies have investigated the combined relationship between GSCM practices, environmental performance, and digital twin technology. Therefore, this study decodes the conceptual framework to create a nexus and justify how digital twin technology can enhance environmental performance through green supply chain management.

Review of the Literature

Conceptualising Digital Twin (DT) technology

Digital twin technology generates a simulation of a data-driven mechanism that obtains instantaneous observations and facilitates businesses to track and scrutinise productivity (Tao et al., 2018). Digital twin integrates a physical product with its virtual representation and validates lifecycle governance of the product (Grieves & Vickers, 2016). This technology also synthesises AI (artificial intelligence), IoT, data analytics, and cloud computing to optimise system evaluation and tracking (Kritzinger et al., 2018).

DT assists organizations in forecasting machine faults and scheduling support activities pre-emptively (Tao & Qi, 2019). As a result, digital twins are extensively employed in production to replicate manufacturing systems and enhance functional efficiency (Negri et al., 2017). It also validates product design by facilitating experimentation and assessing products in a digital domain before manufacturing (Fuller et al., 2020). Furthermore, digital twin simulations facilitate businesses to virtualize system phenomena and enhance operational procedures (Boschert & Rosen, 2016). Therefore, digital twins complement Industry 4.0 by bridging virtual models, physical products, and quantitatively derived decision making (Schleich et al., 2017).

Essence of GSCM

GSCM combines ecological considerations into conventional supply chain activities (Nazir et al., 2024), and also mitigates environmental impact in the product life cycle by GSCM (Khan et al., 2024). GSCM motivates organisations to implement sustainable practices in distribution processes, production, and procurement (Paluš et al., 2024). These approaches assist businesses in enhancing resource efficiency and reducing emissions in supply chains (Yildiz Çankaya & Sezen, 2019). Many industries are adopting GSCM practices due to increasing stakeholder pressure and environmental concerns (Agyabeng-Mensah et al., 2022).

Practices like purchasing, eco-design, green manufacturing, and reverse logistics are included in GSCM (Nazir et al., 2024). These methods focus on minimising pollution, energy consumption, and waste across the supply chain activities (Galdos-Urbizu et al., 2024). Operational and Environmental performance was significantly enhanced by GSCM practices, as shown in recent research (Makhdoom et al., 2025). Therefore, GSCM practices are used in modern supply chains for attaining long-term competitiveness and sustainability (Agyabeng-Mensah et al., 2022).

Relating Digital Twin Technology with GSCM

Existing literature indicates that digital twin technology can assist sustainable supply chain approaches by ensuring real-time supervision and an information-based problem-solving process in the supply chain network (Tao et al., 2018). DT can design digital models of physical activities that allow businesses to examine operational capabilities and resource utilisation with improved efficiency (Fuller et al., 2020). This ability can support organisations to minimise energy consumption, waste, and ecological impact in supply chain activities (Qi & Tao, 2018).

According to Srivastava (2007), GSCM emphasizes synthesizing ecological aspects into supply chain operations such as distribution, logistics, and procurement. Organisations implement green supply chain procedures to enhance ecological outcomes and minimise emission levels throughout the supply chain infrastructure (Zhu & Sarkis, 2004).

Ivanov et al (2021) state that DT can enhance GSCM by delivering continuous monitoring of logistics operations and environmental outcomes. Through digital modelling and future-oriented investigation, digital twins assist organisations to assess manufacturing processes and logistics approaches before applying them in actual operations (Negri et al., 2017). DT also empowers firms to monitor resource utilisation and enhance supply chain operation, which strengthens targets of sustainable development (Schleich et al., 2017).

Relating Digital Twin technology with Environmental Performance

Digital twin assists organisations to track ecological performance through dynamic system information (Grieves & Vickers, 2016). Moreover, digital twin promotes sustainable production by enhancing

resources and energy optimization (Kritzinger et al., 2018). According to Qi and Tao (2018), digital twin technology facilitates firms to measure energy utilisation and mitigate environmental emissions. Furthermore, digital twin modelling supports firms to refine manufacturing mechanisms for effective environmental performance (Tao et al., 2018). Besides this, digital twins strengthen ecological performance through productive machine functioning and predictive maintenance (Uhlemann et al., 2017), and also facilitate data-driven evaluation for environmental decision making (Jones et al., 2020). According to Tao and Zhang (2017), digital twin technology contributes to mitigating environmental pollution and strengthening the product lifecycle. Infrastructure systems elevate environmental supervision and sustainability through digital twins (Batty, 2018). Therefore, digital twins offer technological solutions for sustainable industrial operations and environmental optimization (Fuller et al., 2020).

Nexus building between DT, GSCM and EP

Modern organisations adopt sustainability as a significant tool in supply chain practices for reducing environmental and stakeholder pressure (Fabbe-Costes et al., 2024). GSCM incorporate environmental consideration with activities of the supply chain including sourcing, logistics, and production (Timperi et al., 2024). Existing literature shows that GSCM approaches facilitate businesses to enhance the productivity of resources and curb waste in supply chain operations (Kamble et al., 2022). However, conventional supply chains frequently lack transparency and real-time tracking of organisations' environmental performance (Benhamou et al., 2025).

A digital twin is a part of Industry 4.0 technology, which generates a virtual model of a physical tangible system (Le & Fan, 2024). Simulation and real-time tracking of supply chain activities facilitated by digital twin systems (Jesus et al., 2024). Recent studies indicate that supply chain traceability, coordination, and transparency are assisted through digital twin technology (Abdullahi et al., 2025).

Digital twin enhances the environmental performance of businesses by tracking emissions, energy utilisation, and resource consumption in the supply chain (Arshad et al., 2025). It also mitigates ecological impact in supply chains through sustainable approaches and efficient resource consumption (Resman et al., 2025). Recent research also highlights that adoption of digital twin strengthens GSCM through improved operational planning, predictive analytics, and environmentally conscious decision-making (Elbouzidi et al., 2025). Despite these advancements, limited studies have examined the integrated relationship between digital twin, GSCM, and environmental performance, which highlights the need for further research exploring the nexus among these constructs (Okimi et al., 2025). Consequently, the proposed conceptual framework illustrating the relationship among Digital Twin, GSCM, and Environmental Performance is presented in Figure 1 (Source: Authors' Conceptualization).

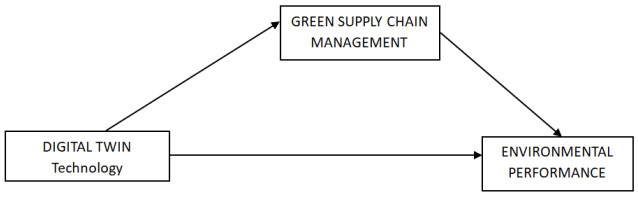

Figure 1: Conceptual Framework Proposed by Author

Research Methodology

This study applies a conceptual approach to construct a framework for understanding the role of digital twin technology on environmental performance through enhancing decision-making and sustainability in green supply chain operations. Qualitative research methods were adopted to comprehend the concepts and existing theories related to GSCM, digital twin, and environmental performance. To attain this objective, a systematic literature review approach was adopted for exploring the academic work. Keywords such as "Environmental Performance", "Digital Twin", and "Green Supply Chain Management" were used for exploring relevant articles. The research is primarily based on secondary data gathered from research repositories, particularly Google Scholar, Scopus, and Web of Science.

The study emphasises the research published in renowned journals in the fields of supply chain management, marketing, manufacturing, information technology, and sustainability, which assures the credibility and quality of the selected literature. Grounded theory techniques and conceptual framework analysis were employed for examining the collected literature. Conceptual framework analysis facilitates the identification of core concepts, interrelations, and theoretical approaches discussed in prior studies and arranges different ideas and variables relevant to the research topic (Jabareen, 2009).

In addition, grounded theory was applied to formulate an intensive conceptual understanding by systematically deducing insights from existing academic

literature (Glaser & Strauss, 1967). Furthermore, this research adopts an inductive approach to interpret the influence mechanism, where observations from prior studies are explored to understand the relationships between environmental performance, digital twin technology, and sustainable supply chain performance.

Findings

Post application of the above-mentioned research methodology, the probable outcomes of the study can be denoted as follows:

- Digital twin technology supports proactive maintenance and error detection, which helps organisations to reduce wastage and enhance operational productivity in manufacturing processes.
- GSCM approaches such as reverse logistics, eco-design, and green purchasing significantly reduce ecological impact across the activities of the supply chain.
- Organisations that enforce GSCM practices enhance both operational and environmental efficiency through minimising emissions and maximising resource utilisation.
- Digital twin technology enhances supply chain monitoring and traceability, and assists organisations in monitoring indicators of the environment, such as carbon emissions and energy consumption.
- Digital twins assist businesses in tracking logistics and production processes in a digital environment, which reduces operational risks and enhances sustainable planning before implementation in the real world.
- Digital twin technology plays a prominent role in strengthening GSCM by providing quantitative insights for environmentally conscious decision-making.
- Digital twins elevate ecological performance by reducing energy usage and industrial pollution through monitoring and data analytics of the system.
- The analysis discloses that the inclusion of digital twin with technologies of Industry 4.0, for instance IoT (Internet of Things), big data analytics, and Artificial Intelligence (AI), strengthens green practices in supply chain management.
- Digital twin technology promotes effective management of resources in supply chains, thereby supporting organisations in achieving the goals of the Sustainable Development Goals.
- The study identifies that the green supply chain practices serve as an important tool through which digital twin technology can affect ecological performance.

Finally, the literature review highlights that digital twin technology has prominent potential to elevate environmental and green supply chain performance. Empirical studies analysing the combined relationship among DT, GSCM and environmental performance remain limited, indicating an important research gap for future investigation.

Discussion

The outcomes of this research support the existing literature that reveals the importance of Digital Twin (DT) in boosting environmental performance and sustainability of the supply chain system. Previous investigations indicate that digital twin technology generates a virtual replica of physical (tangible) hardware, which assists businesses in tracking operations, predicting the disruption of mechanisms, and refining production procedures (Tao et al., 2018; Grieves & Vickers, 2016). Aligned with these studies, the findings reveal that DT assists in maintenance, fault detection, and tracking of operations, which minimizes wastage and enhances efficiency. Existing literature also focuses on how GSCM integrates considerations of environment into supply chain approaches such as procurement, production, and logistics (Srivastava, 2007; Zhu & Sarkis, 2004). The literature further indicates that GSCM practices, including reverse logistics, eco-design, and green purchasing, enhance ecological sustainability and utilisation of resources (Çankaya & Sezen, 2018; Agyabeng-Mensah et al., 2020). The current findings align with the idea that GSCM practices diminish emissions and enhance environmental productivity in the supply chain network.

Moreover, prior research highlights that digital twin technology assists environmental performance through tracking energy usage, pollution, and utilisation of resources (Qi & Tao, 2018; Kritzinger et al., 2018). Similarly, the outcome illustrates that DT facilitates firms to monitor logistics and activities of production digitally, thereby enabling sustainable planning and eco-friendly decision-making. The researcher argues that digital twin technology serves as a facilitating mechanism that reinforces the adoption of GSCM practices. Overall results indicate that unifying digital twin technology and GSCM approaches can enhance businesses'

environmental performance while supporting the targets of sustainable development.

Conclusion

This study explores the impact of digital twin (DT) technology in boosting environmental performance through the embrace of GSCM practices. The research intended to develop a conceptual clarity of how digital twin technology facilitates green supply chain processes and environmental productivity. The outcome of studies demonstrates that digital twin technology enables forecasting, continuous tracking, and enhanced operational observability in the supply chain system. These features assist firms in waste management, maximise resource productivity, and enhance the mechanism of decision-making.

The study also suggests that GSCM approaches such as green purchasing, reverse logistics, and eco-design extensively contribute to reducing ecological impacts across supply chain operations. These techniques encourage management of resources and mitigate pollution, consequently enhancing overall environmental productivity (Srivastava, 2007; Zhu & Sarkis, 2004). Furthermore, the combination of supply chain operations and digital twin technology assists businesses in simulating logistics and production processes virtually, allowing organisations to detect potential bottlenecks and execute ecologically responsible approaches before implementation in the real world (Tao et al., 2018). Collectively, this study indicates that digital twin technology serves as a driving system that facilitates the enforcement of GSCM approaches and enhances environmental performance. Despite this, empirical investigations of the relationship among environmental performance, GSCM, and digital twin remain understudied. Therefore, future studies should explore the empirical validation of this research model in various sectors to further analyse the real-world application of digital twin technology in GSCM.

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