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Digital Twins for Resilient and Sustainable Supply Chains

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Abstract

A supply chain digital twin enables monitoring, analysis and optimization of supply chain operations. It is a virtual representation of the physical supply chain processes, relationships and assets. Ongoing research in the supply chain digital twins highlights its potential to enhance agility significantly (Lulla & Anand, 2023), particularly in complex manufacturing environments which have historically seen low productivity. Studies also explore the integration of digital twins with other technologies like blockchain (Liu et al., 2022) to improve security and transparency. Additionally, the implementation and applications of digital twins in inventory management (Ali et al.,2024) and optimization of perishable supply chain systems (Wu et al, 2023) are explored. This abstract synthesizes research on supply chain digital twins, emphasizing their transformative potential for improved efficiency, resilience, and decision-making.

The adoption of digital twins in supply chain management is continuously evolving, owing to the need for greater visibility, predictability and optimization of complex global supply chain networks.

Keywords: Supply Chain, Digital Twin, Data-driven, Blockchain

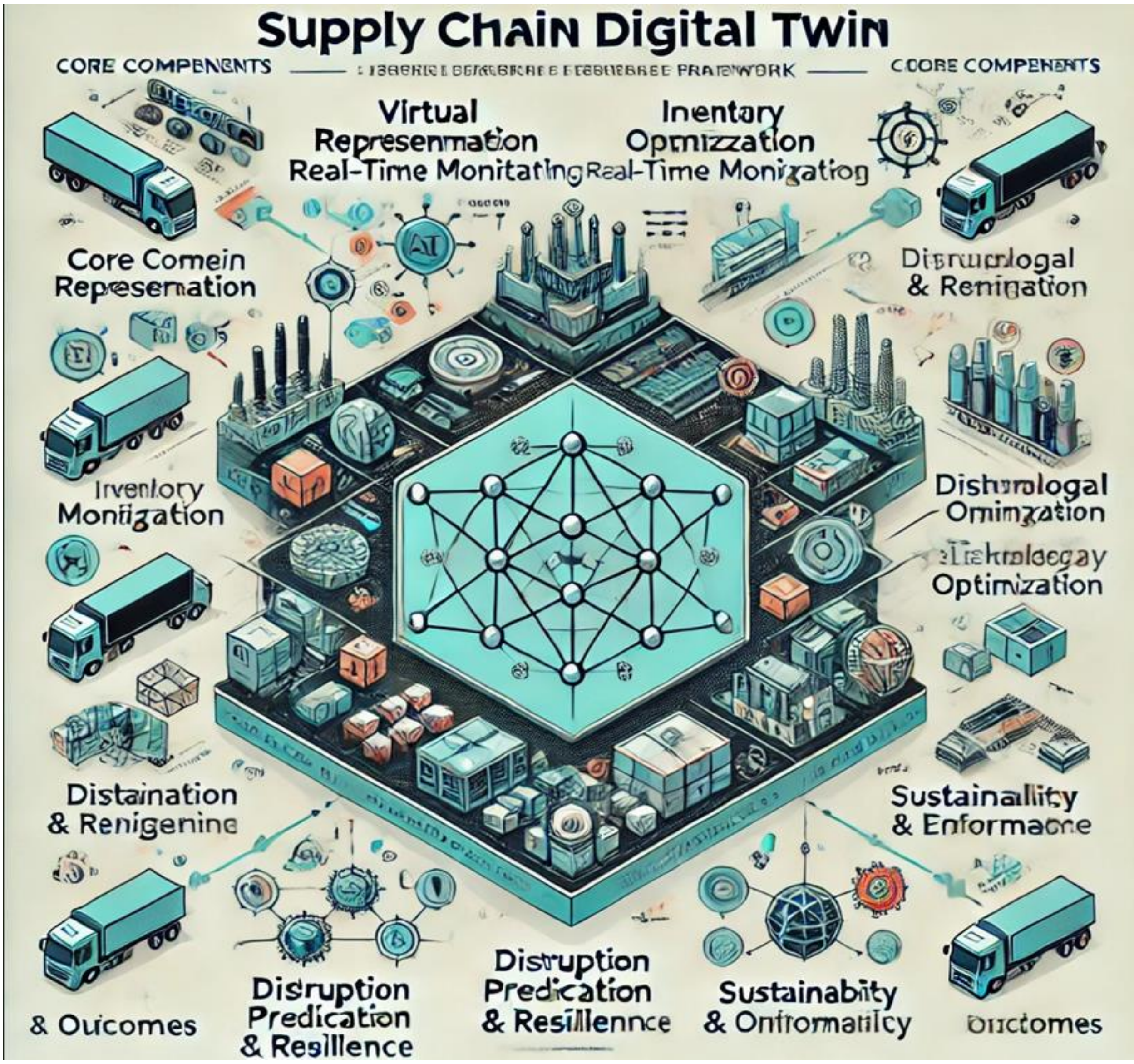
Introduction

The increasing complexity and globalization of modern supply chains necessitate advanced tools and techniques for effective management. Real-time visibility, accurate forecasting, and robust optimization are crucial for maintaining efficiency, resilience, and competitiveness. The concept of a digital twin has emerged as a transformative technology with the potential to revolutionize supply chain operations. A supply chain digital twin is a virtual representation of the physical supply chain, mirroring its processes, relationships, and assets (Saci, 2024). This dynamic model allows for real-time monitoring, analysis, and simulation, enabling businesses to gain deeper insights into their supply chain dynamics and make more informed decisions.

This article delves into the key aspects of supply chain digital twins, exploring their applications, benefits, and challenges. It examines how this technology can enhance various facets of supply chain management, from inventory optimization (Ali et al., 2024) to disruption prediction and mitigation. The introduction also discusses the integration of digital twins with other emerging technologies, such as blockchain (Liu et al., 2022), to further enhance supply chain security and transparency (Jabbar et al., 2020). Finally, it considers the future implications of digital twins and their potential to reshape the landscape of supply chain management.

It examines the practical applications of this technology across various industries, highlighting specific use cases and success stories. For instance, the use of digital twins for real-time robust optimization of perishable supply chain systems is a promising area of research (Wu et al., 2023). Similarly, the role of digital supply chains in enhancing inventory management effectiveness has been investigated within engineering companies (Ali et al., 2024).

Furthermore, it also delves into the technical aspects of creating and implementing a supply chain digital twin. It discusses the data requirements, modeling techniques, and integration challenges associated with building a digital replica of a complex supply chain. The importance of data-driven approaches, such as those employed in evolutionary computation for inventory optimization (Liu & Nishi, 2023), is also highlighted. This page concludes by examining the future research directions and potential advancements in the field of supply chain digital twins, emphasizing their transformative impact on the future of supply chain management. There have been a growing number of studies on supply chain digital twins in recent years. This is a digital dynamic simulation model of a real-world logistics system.



Literature Review

This literature review synthesizes existing research on the application of digital twins (DTs) in supply chain management, highlighting key themes, research gaps, and theoretical underpinnings. The review is structured around four main areas: simulation and digital twins in supply chains, data-driven evolutionary optimization, the theoretical framework of Information Processing Theory (IPT), and the interplay between digital technologies, supply chain resilience, robustness, and sustainable environmental performance.

Simulation and Digital Twins in Supply Chains

Simulation has long been a valuable tool in supply chain management research, enabling the analysis of complex real-world networks. Discrete-event simulation and multi-agent systems are prominent approaches. Discrete-event simulation allows researchers to model and experiment with different scenarios, as demonstrated by Prinz et al. who studied the impact of new transport vehicles on a forest supply system. Multi-agent systems, on the other hand, are well-suited for capturing the complex interactions between various supply chain entities, as highlighted by Dai et al. Recent studies have leveraged multi-agent systems to simulate the behavior of supply chain members under different predefined models.

The emergence of supply chain digital twins represents a significant advancement in this field. A digital twin, defined as a dynamic digital simulation model of a real-world logistics system, offers a near-realistic environment for supply chain simulations. Software like AnyLogistix has become a popular tool for implementing digital twins, particularly for conducting what-if analyses and investigating the impact of disruptions, such as the COVID-19 pandemic, on supply chains. However, a key limitation of current digital twin applications is the lack of robust optimization capabilities. While digital twins can effectively simulate real-world behaviors, they often fall short in providing optimal solutions for decision-making. Existing studies primarily focus on what-if analyses under varying parameter settings, neglecting the crucial aspect of performance optimization. This study addresses this gap by proposing a data-driven evolutionary algorithm to optimize inventory policy using historical data generated by supply chain digital twins.

Data-Driven Evolutionary Optimization

Data-driven evolutionary optimization presents an efficient approach for tackling complex optimization problems characterized by time-consuming objective functions, difficulties in mathematical formulation, or reliance on empirical data. These algorithms can be broadly categorized as offline and online.

Offline data-driven evolutionary optimization constructs surrogate models from existing datasets, without incorporating new data during the optimization process. Numerous offline algorithms have been developed, demonstrating strong performance on benchmark problems. For instance, Mazumdar et al. proposed probabilistic selection approaches for multi-objective problems, while Liu et al. developed a surrogate-assisted algorithm for offline multi-objective problems. Huang and Gong recently proposed a contrastive learning-based approach using classification models for surrogate construction, showing good performance on high-dimensional problems. Offline approaches have also found applications in real-world scenarios, such as blast furnace optimization, beneficiation process optimization, fused magnesium furnace optimization, and airfoil design. Chugh et al. used operational data to build surrogate models for a blast furnace, while Yang et al. proposed a new algorithm for beneficiation processes. Guo et al. studied fused magnesium furnaces, and Li et al. proposed a perturbation-based ensemble surrogate for airfoil design.

Online data-driven evolutionary algorithms, in contrast, actively collect new data and update surrogate models during optimization. This dynamic updating allows online algorithms to potentially achieve better solutions compared to their offline counterparts, due to the increased accuracy of the surrogate models. These algorithms have been successfully applied to large-scale benchmark problems and real-world applications, including wind farm layout optimization, underwater vehicle structural optimization, and feature selection. Long et al. used a general regression neural network for wind farm optimization, while Fu et al. employed a Kriging model for underwater vehicle optimization.

The application of surrogate models is also gaining traction in discrete optimization problems. While traditionally used for continuous optimization, surrogate models have demonstrated their potential in discrete domains. Han and Wang proposed an online algorithm using competitive neighborhood search and random forests for constrained combinatorial problems. Wang and Jin compared random forests and radial basis function networks for trauma system optimization, finding better performance with random forests. Gu et al. proposed a surrogate-assisted evolutionary algorithm for expensive constrained multi-objective discrete optimization problems. While data-driven evolutionary algorithms have been applied across diverse fields, their application to service-constrained inventory optimization for multi-echelon supply chains remains largely unexplored. This research aims to address this gap. Furthermore, the study investigates the universality and robustness of evolutionary algorithms, proposing an ensemble approach to dynamically select appropriate search strategies within differential evolution.

Theoretical Framework: Information Processing Theory (IPT)

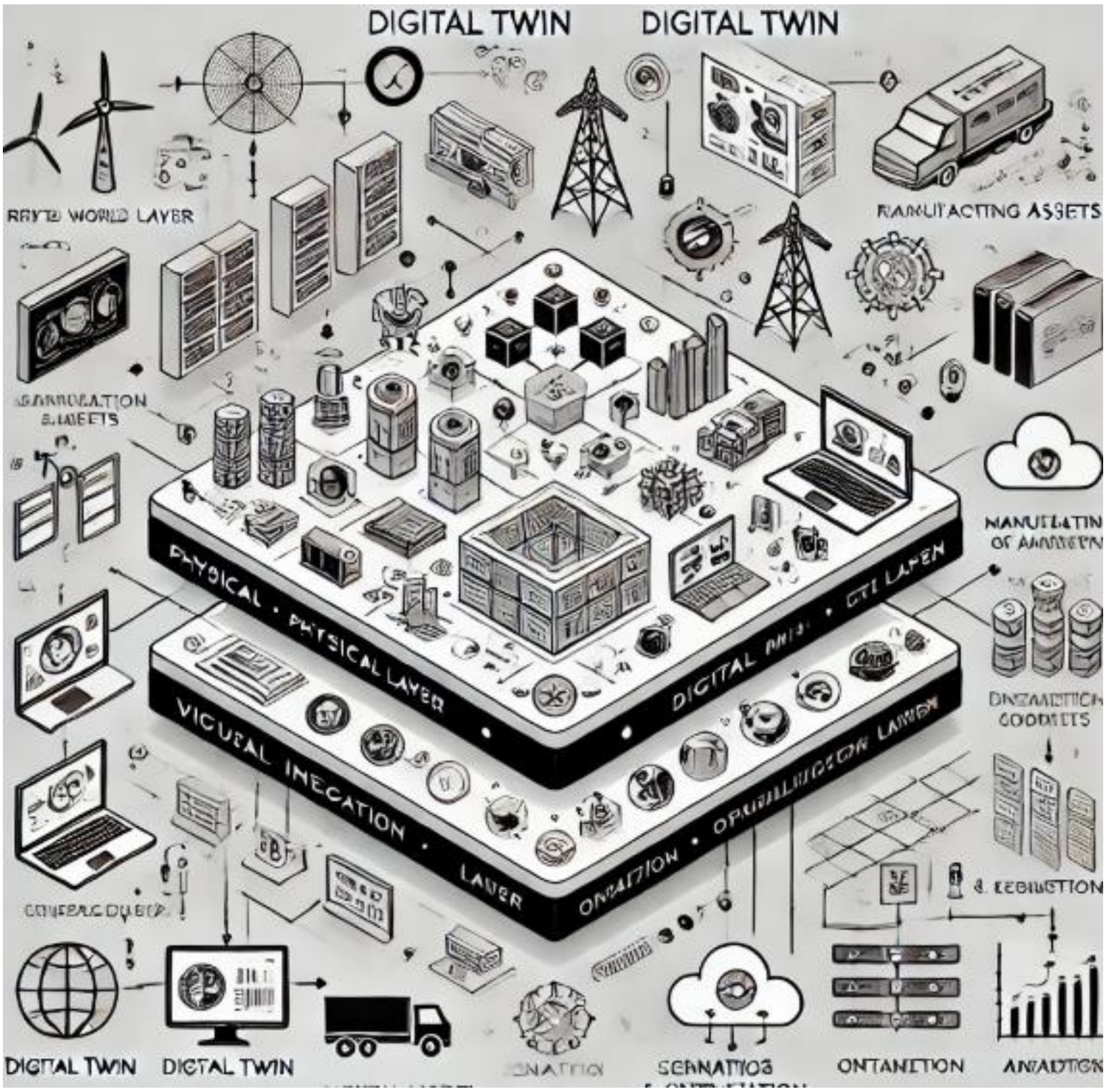
The current research is based on Information Processing Theory (IPT) where organizations operate as information processing systems, reducing uncertainty through information gathering, analysis and utilization. IPT aims to align an organization's information needs with its processing capabilities to achieve optimal performance. The capabilities of an organization are determined by the resource availability and mechanisms established for information gathering, processing and dissemination while the information needs are influenced by the environment. Organizations can adapt to environmental uncertainties by acquiring more high-quality information or enhancing their processing capabilities. Digital twins are considered crucial for information processing, and this study views them as representing the organization's information processing capabilities. Digital supply chains facilitate information exchange, providing access to external data and enabling the supply chain to meet its information needs.

Uncertainty is a constant challenge in supply chain management for both business environment and internal activities due to changing customer demands, competitor actions, and unforeseen disruptions. These can hinder information sharing and collaboration. IPT suggests that enhancing information processing capabilities is crucial for managing these uncertainties and improving organizational performance. This study argues that DTs play a critical role in enhancing IPT capabilitiesfor supply chain resilience and robustness. Additionally, IPT recognizes the reliance on trading partners, which introduces additional randomness and complexity due to variations in supplier capabilities and performance. This emphasizes the need for strong information processing mechanisms to manage these complexities. While previous research has accepted the importance of IPT in understanding supply chain effectiveness, the specific role of DTs in enhancing information capabilities and their subsequent impact on sustainable performance remains an area requiring further investigation.

Digital Technologies, Supply Chain Resilience, Robustness, and Sustainable Environmental Performance

The COVID-19 pandemic has significantly heightened the focus on supply chain resilience (SCRE) and robustness (SCRO), emphasizing their crucial role in adapting to and recovering from disruptions. While SCRO is often defined as the capability to withstandchange, SCRE is viewed as the capacity to bounce back from disruptions and maintain operations amidst challenges. Both SCRE and SCRO are associated with improved resource utilization and operational efficiency. By enhancing information processing, digital twins are expected to increase visibility and transparency within the supply chain. Existing research suggests a positive impact of DTs on both SCRE and SCRO, fortifying the organizations' reactions to and recovery from disruptions. However, potential drawbacks that exist with increased technology presence, such as cybersecurity risks, should also be considered. Other digital technologies, including blockchain, IoT, and cloud computing, have also been linked to improvements in SCRE and SCRO, by enhancing data access, transparency, flexibility, and collaboration. Big data analytics and artificial intelligence play a crucial role in processing data from various DT sources and enhancing customer engagement in sustainable practices. This leads to the formulation of hypotheses regarding the positive impact of digital technologies on SCRE and SCRO.

Furthermore, the relationship between digital technologies and sustainable environmental performance (SEP) is explored. IPT suggests that DTs enhance a firm's information processing capabilities, supporting both environmental and operational decisions. In the context of Industry 4.0, DTs are expected to improve economic and environmental performance through advanced information collection and processing. Efficient information handling through DTs aids in production



Results and Discussion

This article investigated the research on the impact of digital technologies on supply chain resilience (SCRE), robustness (SCRO), and sustainable environmental performance (SEP). The findings offer several key insights and contribute to existing literature in several ways.

The results indicate a positive relationship between DTs and both SCRE and SCRO. This aligns with prior research highlighting the role of DTs in enhancing information visibility, transparency, and real-time data access that are critical for responding to and recovering from disruptions. The ability to access and analyze real-time data combined with the use of big data analytics and artificial intelligence allows organizations to anticipate potential disruptions in the supply chain, adapt quickly to fluctuating conditions, and implement effective recovery strategies. For instance, the integration of IoT sensors and cloud computing enables companies to track inventory levels, monitor transportation routes, and identify potential bottlenecks in real-time. This visibility allows for proactive adjustments to mitigate the impact of disruptions, contributing to both resilience and robustness. However, it is crucial to acknowledge the potential downsides of DT adoption, such as cybersecurity risks. Organizations must invest in robust cybersecurity measures to protect sensitive data and ensure business continuity.

Second, our findings support a positive relationship between DTs and SEP. This suggests that the enhanced information processing capabilities facilitated by DTs contribute to improved operational decision-making leading to environmental sustainability. By integrating environmental considerations into product development, manufacturing processes, and supply chain operations, organizations can reduce their environmental footprint and achieve greater sustainability. For example, DTs can be used to optimize resource utilization that lead to reduced waste generation, and track emissions throughout the supply chain. This aligns with the growing emphasis on environmental sustainability in both academic and business contexts. The ability to collect and analyze data related to environmental performance empowers organizations to identify areas for improvement and implement sustainable practices. However, the substantial investment required for full digital transformation and the potential managerial challenges associated with this shift should not be underestimated. A phased approach, coupled with effective change management strategies, is crucial for successful DT implementation and the realization of its full sustainability potential.

Third, our analysis reveals that SCC moderates the relationship between DTs and both SCRE and SCRO. This suggests that the impact of DTs on resilience and robustness varies depending on the level of supply chain complexity. In highly complex supply chains, the benefits of DTs for resilience and robustness may be amplified due to the increased need for information processing and coordination. Conversely, in less complex supply chains, the impact of DTs may be less pronounced. This finding highlights the importance of considering SCC when designing and implementing DT strategies. Organizations with complex supply chains should prioritize DT investments that enhance information visibility, collaboration, and real-time decision-making. Furthermore, understanding the specific dimensions of SCC (e.g., structural vs. dynamic) and their interplay with DTs is crucial for developing targeted interventions.

Fourth, our results demonstrate the mediating roles of SCRE and SCRO in the relationship between DTs and SEP. This implies that the positive impact of DTs on SEP is, at least partially, realized through their influence on resilience and robustness. Organizations that leverage DTs to enhance their resilience and robustness are better positioned to achieve sustainable environmental performance. This finding underscores the interconnectedness of these three concepts and highlights the importance of a holistic approach to supply chain management. By investing in DTs that enhance both resilience and robustness, organizations can create a virtuous cycle that leads to improved environmental performance. For example, a resilient supply chain is better equipped to handle disruptions that could negatively impact environmental performance, such as delays in the delivery of environmentally friendly materials or disruptions to recycling processes.

This study makes several important contributions to the literature. First, it provides empirical evidence for the positive impact of DTs on SCRE, SCRO, and SEP, extending previous research in this area. Second, it highlights the moderating role of SCC in the relationship between DTs and resilience/robustness, offering a nuanced understanding of the interplay between these concepts. Third, it demonstrates the mediating roles of SCRE and SCRO in the relationship between DTs and SEP, revealing the mechanisms through which DTs contribute to improved environmental performance. Finally, the study's focus on a developing market context, specifically Egypt, provides valuable insights into the challenges and opportunities associated with DT adoption in such settings.

However, this study also has some limitations. The cross-sectional nature of the data limits our ability to draw causal inferences. Future research could employ longitudinal studies to examine the dynamic relationships between the variables over time. Furthermore, the study relies on self-reported measures, which may be subject to bias. Future research could incorporate objective measures of supply chain performance and environmental impact to enhance the validity of the findings. Finally, the study focuses on a specific industry context, which may limit the generalizability of the findings. Future research could explore the impact of DTs in other industries and across different cultural contexts.

Despite these limitations, this study provides valuable insights into the role of DTs in enhancing supply chain performance, resilience, robustness, and sustainability. Our findings have important implications for managers seeking to leverage DTs to improve their supply chain operations and achieve their sustainability goals. By understanding the complex interplay between DTs, SCC, SCRE, SCRO, and SEP, organizations can develop more effective strategies for navigating the challenges of the modern business environment and creating a more sustainable future. Future research could explore the specific DT capabilities that are most impactful for different types of supply chains and investigate the role of organizational culture and leadership in facilitating successful DT adoption. Additionally, exploring the potential of DTs to contribute to circular economy initiatives and the development of closed-loop supply chains represents a promising avenue for future research.

Conclusion

This study investigated the multifaceted relationships between digital technologies (DTs), supply chain resilience (SCRE), robustness (SCRO), and sustainable environmental performance (SEP), with a focus on the mediating roles of SCRE and SCRO and the moderating influence of supply chain complexity (SCC). Our findings offer several key contributions to existing literature and provide valuable insights for practitioners.

First, we confirmed the positive impact of DTs on both SCRE and SCRO, aligning with previous research that highlights the role of DTs in enhancing information visibility, transparency, and real-time data access. These capabilities are crucial for effective disruption response and recovery. However, we also emphasized the importance of addressing potential cybersecurity risks associated with DT adoption.

Second, our results support the positive relationship between DTs and SEP, suggesting that improved information processing through DTs contributes to better environmental and operational decision-making. This underscores the potential of DTs to drive sustainability initiatives within supply chains.

Third, our analysis revealed the moderating role of SCC in the relationship between DTs and resilience/robustness. This suggests that the effectiveness of DTs varies depending on the complexity of the supply chain, highlighting the need for tailored DT strategies.

Fourth, we demonstrated the mediating roles of SCRE and SCRO in the relationship between DTs and SEP, indicating that the positive influence of DTs on environmental performance is partially realized through their impact on resilience and robustness.

These findings contribute to the literature by providing empirical evidence for the complex interplay between DTs, SCRE, SCRO, and SEP. They also highlight the importance of considering SCC as a moderating factor in this relationship. Furthermore, the study's focus on a developing market context, specifically Egypt, offers valuable insights into the adoption of DTs in such settings.

From a practical perspective, our findings offer several implications for managers. Organizations should prioritize DT investments that enhance information visibility, collaboration, and real-time decision-making, particularly in complex supply chains. They should also develop robust cybersecurity measures to mitigate potential risks associated with DT adoption. Furthermore, a holistic approach that considers the interconnectedness of resilience, robustness, and sustainability is crucial for maximizing the benefits of DTs.

While this study offers valuable contributions, it also has limitations. The cross-sectional nature of the data limits causal inferences. Future research could employ longitudinal studies to examine the dynamic relationships between the variables. The reliance on self-reported measures also presents a potential limitation. Future research could incorporate objective measures of supply chain performance and environmental impact. Finally, the industry-specific focus may limit generalizability. Future research could explore other industries and cultural contexts.

Despite these limitations, this study provides a strong foundation for understanding the role of DTs in enhancing supply chain performance and sustainability. Future research could delve deeper into the specific DT capabilities that are most impactful for different supply chain types and investigate the influence of organizational culture and leadership on successful DT adoption. Exploring the potential of DTs for circular economic initiatives and closed-loop supply chains also represents a promising direction for future research. Ultimately, this study contributes to a growing body of knowledge that emphasizes the transformative potential of DTs in creating more resilient, robust, and sustainable supply chains.

References

1. Ali, A. A. A., Fayad, A. A. S., Alomair, A., & Naim, A. S. A. (2024). The role of digital supply chain on inventory management effectiveness within engineering companies in Jordan. *Sustainability, 16*(18), 8031. https://doi.org/10.3390/su16188031
2. Jabbar, S., Lloyd, H., Hammoudeh, M., Adebisi, B., & Raza, U. (2020). Blockchain-enabled supply chain: Analysis, challenges, and future directions. *Multimedia Systems, 27*(4), 787. https://doi.org/10.1007/s00530-020-00687-0
3. Liu, J., Yeoh, W., Qu, Y., & Gao, L. (2022). Blockchain-based digital twin for supply chain management: State-of-the-art review and future research directions. *SSRN Electronic Journal*. RELX Group (Netherlands). https://doi.org/10.2139/ssrn.4113933
4. Liu, Z., & Nishi, T. (2023). Data-driven evolutionary computation for service-constrained inventory optimization in multi-echelon supply chains. *Journal of Industrial Engineering, 10*(1), 825.
5. Lulla, S., & Anand, D. (2023). Can a supply chain digital twin make you twice as agile? *EY Insights*. Retrieved from https://www.ey.com/en_gl/advanced-manufacturing/can-a-supply-chain-digital-twin-make-you-twice-as-agile
6. Saci, S. (2024). What is a supply chain digital twin? *Towards Data Science*. Retrieved from https://towardsdatascience.com/what-is-a-supply-chain-digital-twin-e7a8cd9aeb75?gi=514763c56c3f

7. Wu, Y., Zhang, J., Li, Q., & Tan, H. (2023). Research on real-time robust optimization of perishable supply-chain systems based on digital twins. *Sensors, 23*(4), 1850. https://doi.org/10.3390/s23041850