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DIGITIZING LEAN SUPPLY CHAIN: THE STRATEGIC ROLE OF DIGITAL TWIN IN OPERATIONAL EXCELLENCE

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Abstract:

Digital Twin (DT) technology can be strategically integrated with Lean Supply Chain Management (LSCM) to improve operational excellence. A narrative literature review was undertaken using PRISMA methods to filter over 200 peer-reviewed articles (2020–2025) using Scopus, Web of Science, and ScienceDirect. The study uses the Technology Organization Environment (TOE) theory to describe a moderation paradigm in which technological readiness moderates the relationship between DT adoption and Supply Chain Performance. The results imply that DT-enabled lean systems offer better visibility, predictive analytics, and scenario modelling than reactive solutions. Integration makes lean proactive, improving efficiency, resilience, and sustainability. The paradigm fills a crucial research vacuum by explaining how DT improves lean's success while accounting for organisational and technology factors. Empirical testing is needed for this conceptual investigation, which will lay the groundwork for Structural Equation Modelling. Management should link DT expenditures with organisational preparedness to prevent digital waste and maximise strategic value, according to the report. This work advances academic scholarship and managerial practice by integrating DT, lean supply chain methods, and TOE contingencies into a theoretical model. It shows how digital technologies and lean concepts

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can digitise operational excellence and create more flexible, future-ready supply chains.

Keywords:

Digital Twin; Lean Supply Chain Management; Resource-Based View; Technology–Organization–Environment; Supply Chain Performance; Operational Excellence; Structural Equation Modeling.

Introduction

Global supply chains are facing unprecedented turbulence, marked by rising demand volatility, environmental constraints, and geopolitical disruptions that threaten continuity and resilience (Ivanov & Dolgui, 2022). The COVID-19 pandemic exposed structural fragilities across global networks, from raw material shortages to last-mile delivery breakdowns, underscoring the urgent need for adaptive and data-driven operations (Queiroz et al., 2022). At the same time, societal expectations for sustainability are pressuring firms to reduce their carbon footprint, optimize resource utilization, and meet net-zero targets (Kamble et al., 2023). These challenges demand more than incremental improvement — they require a paradigm shift in how supply chains are designed, monitored, and optimized.

Lean Supply Chain Management (LSCM) has long been celebrated for its focus on waste elimination and continuous improvement, offering tools such as value stream mapping, just-in-time production, and kaizen (Buer et al., 2021). Yet traditional lean systems, which rely heavily on historical data and static planning, struggle to respond to real-time disturbances and complex multi-tier supplier networks (Tortorella et al., 2023). The limitations of conventional lean practices reveal a critical gap: how can organizations maintain lean efficiency while becoming more resilient and predictive in a volatile environment.

Digital Twin (DT) technology defined as a dynamic, virtual representation of physical assets and processes synchronized with real-time data has emerged as a potential game-changer (Tao et al., 2023). DTs enable scenario modelling, predictive analytics, and what-if simulations that empower decision-makers to detect bottlenecks and mitigate risks before they materialize (Ivanov, 2023). When integrated with lean principles, DTs can amplify the power of continuous improvement by providing end-to-end visibility, faster root-cause analysis, and data-driven kaizen cycles (Guo, 2025).

This study seeks to bridge this theoretical and practical gap by conceptualizing a framework that links DT adoption with lean supply chain practices to enhance supply chain performance, resilience, and sustainability. In doing so, it contributes to the growing discourse on digital transformation in operations management and offers a roadmap for organizations seeking to digitize operational excellence.

Literature Review

LSCM extends lean thinking to the entire value chain, focusing on synchronized flow, waste elimination, and responsiveness to customer demand (Womack & Jones, 2020). Modern LSCM research emphasizes its role in achieving agility and sustainability simultaneously, a paradigm sometimes termed "Lean-Green" supply chain (Sharma et al., 2023). Despite its strengths, lean systems are often criticized for their vulnerability to disruption due to reduced buffers and just-

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in-time inventory (Ivanov, 2021). This tension between efficiency and resilience has prompted scholars to explore hybrid lean-resilient systems (Ali & Gölgeci, 2022).

DT is increasingly recognized as a cornerstone of Industry 4.0, offering a live, data-rich digital representation of assets, processes, and networks (Tao et al., 2023). Its application in supply chains spans network design, logistics simulation, inventory optimization, and predictive risk management (Liu et al., 2024). For example, DT-enabled logistics control towers integrate IoT and AI to monitor shipment conditions, predict delays, and re-route flows in real time, improving service levels and reducing costs (Verdouw et al., 2022).

Recent studies show that DT can act as an enabler of lean practices by reducing information asymmetry and enhancing problem-solving speed (Guo, 2025). By simulating value streams, organizations can identify non-value-adding activities before physical implementation, thus lowering experimentation cost and risk. DT supports kaizen through virtual testing of process changes and continuous feedback loops (Kamble et al., 2023). Empirical evidence from manufacturing and logistics sectors indicates that DT adoption is positively associated with inventory turnover, lead time reduction, and throughput performance (Liu et al., 2024).

The Resource-Based View (RBV) posits that competitive advantage arises from valuable, rare, inimitable, and non-substitutable resources (Barney, 1991). DT capabilities, including real-time data analytics and predictive modeling, can be seen as strategic resources that enhance operational excellence (Ivanov, 2023). The Technology–Organization–Environment (TOE) framework further explains adoption drivers, emphasizing technological readiness, organizational culture, and environmental pressure as key factors influencing DT implementation (Tornatzky & Fleischer, 2021). Combining RBV and TOE allows researchers to capture both the internal capability-building and external institutional drivers of DT-enabled LSCM.

Most studies treat lean and digitalization separately; few quantify the combined impact of DT enabled lean on SCP using robust mediation–moderation models. Moderating effects of digital maturity remain under explored, leaving a clear empirical gap (Queiroz et al., 2022).

Conceptual Framework

Digital Twin (DT). DT is conceptualized as a higher-order capability that combines three critical sub-dimensions: (1) Real-time data acquisition through IoT sensors, RFID, and cyber-physical systems; (2) Advanced analytics and AI models for predictive maintenance, demand forecasting, and network optimization; and (3) Physics-based simulation and visualization, enabling managers to run virtual experiments before implementing physical changes. Together, these elements create a closed-loop system of sensing, thinking, and acting that transforms static supply chains into adaptive, self-learning networks

Lean Practices (LP). Lean practices represent the operational routines and process disciplines aimed at eliminating waste (muda) and creating value. Core routines include Value Stream Mapping (VSM) for process visibility, Just-in-Time (JIT) for inventory optimization, Kanban systems for pull-based scheduling, standardized work to reduce variability, and continuous improvement (kaizen) cycles. In this model, LP acts as the primary mechanism that operationalizes insights generated by DT, translating digital intelligence into tangible process improvements.

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Supply Chain Performance (SCP). SCP is modeled as a second-order reflective construct capturing three strategic dimensions:

- Efficiency: reduction of lead times, improved order fill rate, lower logistics cost-to-serve, and higher inventory turns.
- Resilience: ability to anticipate, absorb, and recover from disruptions measured through time-to-recover (TTR), service continuity under shocks, and flexibility to reconfigure networks.
- Sustainability: environmental and social performance outcomes including reduction in greenhouse gas emissions, energy consumption, and material waste.

This multidimensional conceptualization ensures that performance measurement transcends cost-efficiency to include robustness and long-term viability.
TOE Readiness. TOE readiness is defined as a composite contingency encompassing three spheres:

- Technological context: maturity of IT infrastructure, data integration capability, and availability of analytics tools.
- Organizational context: leadership support, cross-functional collaboration, employee skills, and lean culture.
- Environmental context: regulatory pressure, market volatility, and customer sustainability demands.

TOE acts as a moderator that shapes the strength of DT's influence on LP and SCP, positing that organizations with high readiness will extract greater benefits from DT-enabled lean initiatives.

Figure 1: The Conceptual Framework

Boundary Conditions. Effects may be weaker in low variety, stable environments where simple lean controls suffice; stronger in high mix, high uncertainty contexts where predictive capability is critical.

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Methodology

This conceptual paper utilised a systematic narrative synthesis protocol to guarantee methodological reproducibility and thematic clarity. The literature review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and employed the four-phase approach outlined by Popay et al. (2006) for narrative synthesis, which includes (1) systematic search, (2) study selection and data extraction, (3) thematic clustering and textual synthesis, and (4) critical reflection and conceptual integration.

Search Protocol.

Databases such as Scopus, Web of Science, and ScienceDirect were systematically searched using Boolean combinations of the terms “digital twin,” “lean supply chain,” “Industry 4.0,” “supply chain performance,” and “resilience.” A total of 218 peer-reviewed articles published from 2020 to 2025 were identified in the initial search. Following the assessment for relevance, duplication, and quality, 164 articles were selected for full-text review. A total of 87 articles were retained for final synthesis based on inclusion and exclusion criteria, which included peer-reviewed status, English language, conceptual or empirical rigour, and clear relevance to Digital Twin (DT), Lean Supply Chain (LSC), or Supply Chain Performance (SCP). The PRISMA flow diagram illustrates this process.

Table 1. Thematic Clustering of Reviewed Studies (n = 87)

Cluster	Primary Focus	Representative Themes	Sample of Key References (2020–2025)	Number of Studies (n)
Cluster 1: Digital Twin (DT)–Focused Studies	Exploration of digital twin technologies, architectures, and integration in logistics and manufacturing systems.	Real-time monitoring, simulation analytics, predictive maintenance, and IoT-driven visibility.	Tao et al. (2023); Ivanov (2023); Verdouw et al. (2022); Liu et al. (2024)	32
Cluster 2: Lean Supply Chain (LSC)–Focused Studies	Application of lean principles and waste elimination across value chains.	Value Stream Mapping, Just-in-Time (JIT), Kaizen, Lean–Green integration, and resilience trade-offs.	Buer et al. (2021); Tortorella et al. (2023); Sharma et al. (2023); Kamble et al. (2023)	29
Cluster 3: Supply Chain Performance (SCP)–Focused Studies	Measurement and improvement of efficiency, resilience, and sustainability outcomes.	Lead-time reduction, service-level improvement, carbon reduction, and flexibility metrics.	Ivanov & Dolgui (2022); Queiroz et al. (2022); Ali & Gölgeci (2022)	26
Total				87

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Thematic clustering refers to the process of grouping related concepts or topics based on shared themes or characteristics. The selected studies were categorised into three thematic clusters for synthesis.

- Studies focused on digital twin technologies (n = 32) examine their architecture and applications within logistics and manufacturing.

- Studies centred on lean methodologies (n = 29) highlighting lean principles, waste reduction, and ongoing enhancement throughout value chains.

- Studies focused on SCP (n = 26) examine operational, resilience, and sustainability outcomes in supply chain contexts.

The clusters were cross-compared to identify intersections where digitalisation enhances lean-driven performance improvement, establishing the theoretical foundation for the proposed mediation–moderation framework.

Synthesis Methodology.

In accordance with Popay et al. (2006), the synthesis integrated textual and conceptual analysis to create a narrative that connects DT capabilities with lean operational mechanisms and performance outcomes. The methodology achieved conceptual saturation and facilitated the integration of theories through the Resource-Based View (RBV) and Technology–Organization–Environment (TOE) frameworks. Hair et al. (2022) offered methodological guidance for future empirical validation through the use of Structural Equation Modelling (SEM).

Empirical Framework For Future Validation.

It is advisable to conduct future empirical testing utilising SEM with AMOS or SmartPLS, ensuring a sample size of $N \geq 200$. Measurement model parameters must adhere to reflective indicator standards, specifically outer loadings of at least 0.708, composite reliability (CR) of 0.70 or higher, average variance extracted (AVE) of 0.50 or more, and Heterotrait-Monotrait ratio (HTMT) below 0.85. Structural model evaluation should incorporate bootstrapping with a minimum of 5,000 resamples and include reporting of R^2, f^2, Q^2, and fit indices such as CFI, TLI, and RMSEA. It is recommended to incorporate control variables, including firm size, industry, and complexity, to enhance the robustness of the model.

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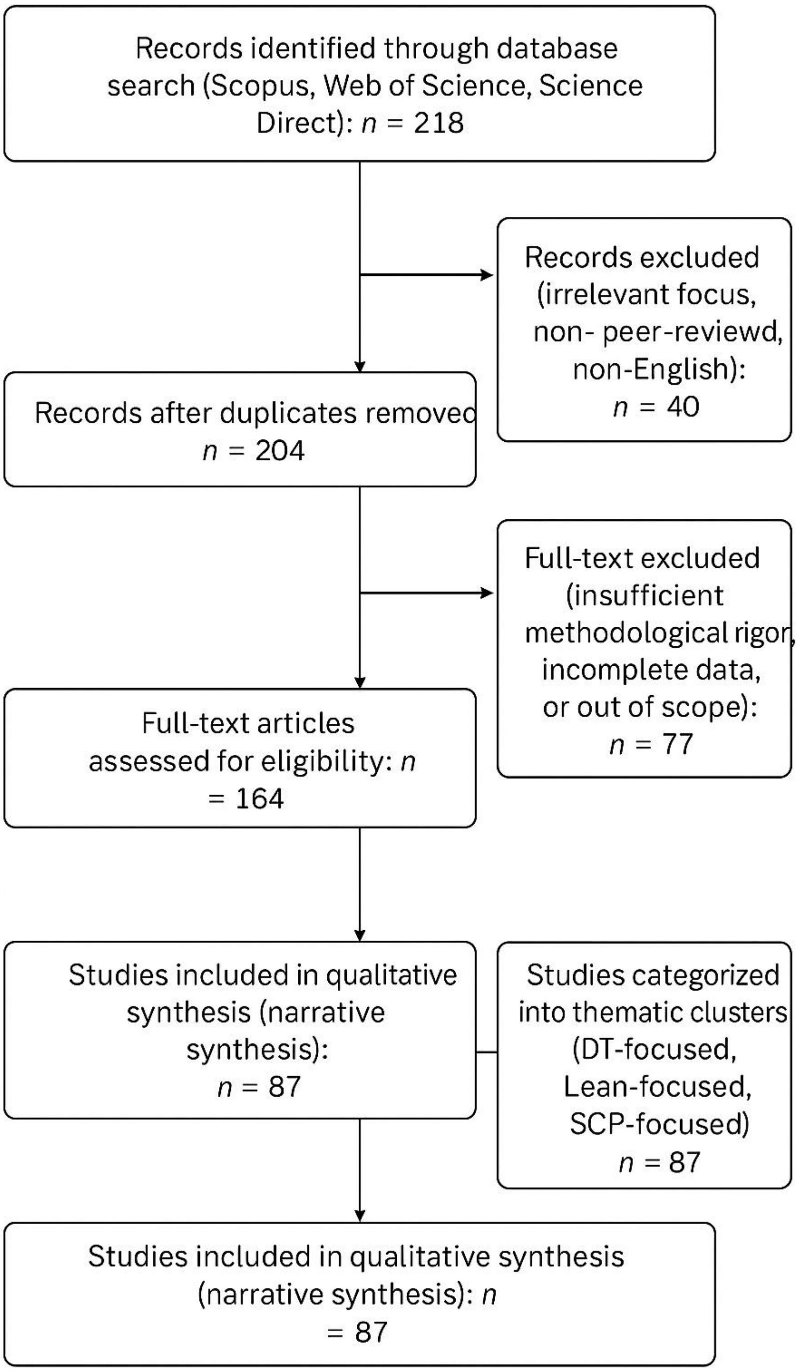
Figure 1. PRISMA Flow Diagram of Literature Screening Process



Note. The PRISMA protocol followed the four-phase structure of Popay et al. (2006): (1) identification, (2) screening, (3) eligibility, and (4) inclusion.

Discussion

This conceptual synthesis supports the consensus that digitalisation improves the effectiveness of lean principles when aligned with organisational readiness and contextual factors. Recent studies (Zhang et al., 2023; Tortorella et al., 2023; Kamble et al., 2023) indicate that digital tools, including Digital Twin (DT) systems, enhance the conventional framework of Lean Supply Chain Management (LSCM) by facilitating real-time visibility, predictive analytics,

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and adaptive decision-making. This integration converts lean from a reactive improvement framework into a proactive, data-informed capability that anticipates and addresses disruptions prior to their escalation.

This synthesis supports the Resource-Based View (RBV) claim that digital transformation (DT) capabilities are valuable and inimitable resources that can lead to sustained competitive advantage (Ivanov, 2023). The Technology–Organization–Environment (TOE) framework delineates the conditions necessary for the emergence of advantages, highlighting the importance of technological maturity, cross-functional coordination, and environmental turbulence (Tornatzky & Fleischer, 1990). The combination of these perspectives elucidates why firms exhibiting elevated levels of digital and organisational readiness are likely to achieve enhanced performance outcomes from lean–digital integration.

This study significantly elaborates on the lean efficiency–resilience paradox, a persistent tension in operations management. Lean systems improve efficiency by reducing waste and variability; however, they often decrease buffers and redundancy, which are critical for resilience in times of crisis. Empirical evidence from the COVID-19 pandemic highlights this dilemma: highly lean global supply chains experienced significant disruptions due to border closures and demand shocks, while hybrid models that integrated lean discipline with digital sensing technologies demonstrated a more rapid recovery (Ivanov & Dolgui, 2022; Queiroz et al., 2022). The paradox necessitates a redefinition of "lean" from a perspective of fragility to one of adaptive capability, particularly when enhanced by digital transformation-enabled foresight.

Recent studies (Guo, 2025; Liu et al., 2024) demonstrate that DT-driven simulations enable organisations to virtually test various "what-if" scenarios, effectively balancing cost efficiency and risk preparedness. Embedding simulation analytics into lean improvement cycles enables firms to assess the impacts of process modifications prior to implementation, thereby attaining dynamic efficiency, which represents a balance between stability and agility. This reframing corresponds with recent post-pandemic studies highlighting that the future of operational excellence is rooted in resilient lean practices, wherein digital intelligence enhances process discipline.

The proposed framework outlines a sequential adoption pathway: initially stabilising the data infrastructure, subsequently institutionalising lean routines, and ultimately scaling DT-enabled analytics. This sequencing reduces "digital waste," which occurs when companies invest in technologies lacking adequate process maturity or alignment. This perspective aligns with Hair et al. (2022), asserting that capability building must occur prior to increasing model complexity to facilitate significant empirical validation.

This study addresses a significant theoretical gap by integrating capability-based and contingency-based reasoning. It enhances the comprehension that DT-enabled lean systems are not only efficient but also intelligently adaptive, able to maintain performance in both stable and volatile environments. This conceptual integration establishes a robust foundation for subsequent empirical validation through Structural Equation Modelling (SEM) and cross-industry comparisons.

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Conclusion

This study integrates Digital Twin (DT) and Lean Supply Chain Management (LSCM) within a cohesive Resource-Based View (RBV) and Technology–Organization–Environment (TOE) framework. DT is regarded as an advanced capability that facilitates the transformation of data into ongoing improvement via lean practices, whereas TOE readiness accounts for performance variability among firms.

The integration of digital intelligence with lean principles addresses the efficiency–resilience paradox, transforming lean from a fragile approach to an adaptive one. Sustainable operational excellence relies on the integration of process rigour and predictive analytics.

The framework theoretically integrates capability building with contextual contingencies within a unified model. This framework assists managers in enhancing data foundations, institutionalising lean practices, and expanding digital transformation analytics to create adaptive, high-performing supply chains.

Future Research

This study provides a solid conceptual framework; however, future research should empirically test and expand its propositions using various methodological approaches.

Initially, the implications for management require further analysis. Future research may investigate the impact of different levels of digital transformation maturity on the return on investment (ROI) associated with lean initiatives and digital transformation projects. Quantifying these thresholds assists managers in prioritising digital investments based on operational readiness and anticipated payback periods. Longitudinal studies may elucidate the evolution of DT-driven learning curves as firms transition from pilot projects to enterprise-wide implementation.

Researchers should expand the framework to incorporate sustainability integration, establishing a direct connection between DT-enabled lean systems and the United Nations Sustainable Development Goals (SDGs). DT applications in logistics optimisation, energy efficiency, and waste reduction align with SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Empirical investigation of these connections will enhance the theoretical framework and illustrate the role of digital lean systems in advancing global sustainability goals.

Future research should examine the nonlinear relationship between efficiency and resilience across various industries and regions, assessing the impact of digital simulation on the conventional lean trade-off in crisis situations. Experimental simulation studies or digital twin-based scenario modelling may offer insights into the adaptive thresholds of supply chain robustness.

Future research must confirm the statistical validity of the proposed model and elucidate its strategic and sustainability implications, demonstrating how digital transformation-enabled lean transformation can foster competitive advantage and promote planetary stewardship.

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