

Exploring the Role of Digital Twin Technology in Enhancing Supply Chain Resilience: A Conceptual Framework

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Abstract: This research seeks to construct a more comprehensive conceptual framework that integrates enabling technologies, critical business activities, and outcomes of resilience to clarify the mitigating and performance boosting impacts of Digital Twins (DTs) on supply chains. The researcher reviewed literature and consulted diverse theories and scholars in order to devise the framework that addresses the problem. The framework was based on socio-technical systems theory, the Resource-Based View, and complexity theory to show the impacts of technology on the architectural evolution of the structures that make up a supply chain network. Its key elements, “inputs, processes and outcomes,” were given and systematized about the dynamic interactions of supply chain resilience and digitized twin technology. The framework’s digital enablers— the IoT, AI, and high-fidelity simulation platforms— are also important to real-time monitoring, risk evaluation, scenario modelling, and simulation of critical functions which bolster the resilience traits of responsiveness, operational flexibility, and risk mitigation. The study underlines the contribution of DTs to enhanced situational awareness and, therefore, more effective and strategic oversight in decision-making on supply chain management as a whole. Therefore, the research addresses a significant gap in the literature by bridging functionality of digital twinning with the assemblage of resilience genes and by emphasizing the framework’s overriding digital resilience. Digitized two-dimensional replicas of core components of a business system, commonly known as digital twins, provide supply chain personnel with a systematic technique for incremental realization of anticipatory breach mitigation strategy implementation guided by comprehensive risk assessment and predictive scenario contingency strategy planning.

Keywords: *Digital Twin Technology, Supply Chain Resilience, Real-Time Monitoring, Risk Mitigation*

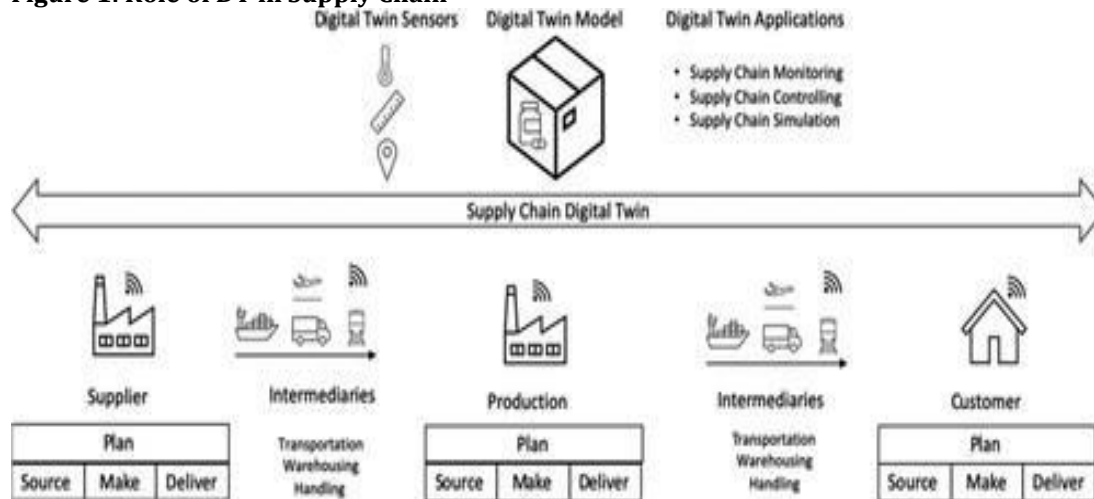
1. Introduction

The prevailing world environment now presents us with tightly interwoven crises: ever-more-frequent climatic disasters, deepening geopolitical tensions, and pandemics that reverberate through provision networks (Vatumalae, Rajagopal, & Sundram, 2020; Wong Chee, Sundram, Bakar, & Narayanan, 2024; Zolait et al., 2019; Zulfakar et al., 2019). Each perturbation underscores that provision networks must transcend remedial handbooks in favour of genuine distributional agility—the ability to detect, redirect, and recalibrate while critical operations remain undisturbed (Chowdhury & Quaddus, 2017). Architectures optimised for minimal cost alone have revealed vulnerabilities in extremis, necessitating that strategic infrastructures be reconfigured around the cadence of disruption. Into this gap, the Digital Twin (DT) paradigm advances. A DT offers an ever-updating mirror of any tangible asset, process, or entire system, thus merging real-time sensor data with cyber-analytic and experimental environments (Tao et al., 2019). Within supply chain ecosystems, these living threads amplify exposure to underlying dynamics, sharpen predictive signal-to-noise ratios, and empower pre-emptive governance. By sculpting high-fidelity virtual analogues of entire logistics arteries, organizations can probe thousands of stress permutations, spotlight latent vulnerabilities, and engineer fortified, adaptive supply chains in real time (Ivanov & Dolgui, 2021).

Despite their enticing potential, the specific role of Digital Twins in bolstering supply chain resilience has not yet attracted much focused attention in academic discourse. Existing studies analyzing their deployment in manufacturing environments and across product lifecycles highlight an obvious gap: there are few comprehensive models that connect Digital Twin capabilities directly to resilience-oriented supply chain strategies (Zhong et al., 2022). This underscores the demand for a deeper understanding of how DTs can be employed in a purposeful, systemic manner to defend supply chains against a range of disruptive shocks. Accordingly, we present a conceptual framework designed to demonstrate how Digital Twin technology can be harnessed to address and alleviate supply chain vulnerabilities. The framework aspires to serve as an actionable, integrative roadmap for practitioners eager to embed DTs into their resilience initiatives, drawing on an extensive literature review and fusing it with insights from cutting-edge technological developments.

Figure 1 presents a comprehensive view of a Supply Chain Digital Twin (SCDT), which integrates digital technologies throughout the entire supply chain, from suppliers to customers. It begins with digital twin sensors that collect real-time data such as location and environmental conditions. This data feeds into a digital twin model, which is a virtual representation of the physical supply chain. The model enables three key digital twin applications: monitoring (to observe real-time supply chain activities), controlling (to dynamically manage and respond to issues), and simulation (to predict and optimize future scenarios). The supply chain process is segmented into five key components: supplier, intermediaries, production, intermediaries (again), and customer. Each component follows the core supply chain functions—plan, source, make, and deliver—while intermediaries also manage transportation, warehousing, and handling. The digital twin framework thus provides end-to-end visibility, responsiveness, and efficiency across the supply chain ecosystem.

Figure 1: Role of DT in Supply Chain



This article is structured as follows. In the supply chain resilience and the Digital Twin technology review, the literature review section reviews relevant literature. In the methodology section, the approach taken to develop the proposed conceptual framework is described. In the conceptual framework section, the model that is proposed is presented along with all of its parts and their relations. In the discussion section, the implications of the framework for theory and practice are examined. Lastly, the conclusion rounds up the work and provides a synthesis of the findings while indicating promising avenues for further research.

2. Literature Review

The modern-day unpredictable natural calamities, political calamities, and pandemics serve as stressors toward a business's continual function (Mkumbo et al., 2019). These issues have instigated a shift toward comprehensive study centered around a business's Supply chain and how resilient its systems and processes are, keeping core functions uninterrupted and operative (Handra and Sundram, 2023). Supply chain resilience refers to a system's overall ability to prepare, adjust, and recover proactively while Agile, adaptive, proactive, and reactive core functions remain unhampered, uninterrupted, and undisturbed while supporting core

functions uninterrupted. Resilience encompasses four core themes, namely agility, adaptability, robustness, and visibility. “Agility” (Dubey et al., 2019) speaks toward the system’s ability to refractor and operationally shift to realign to set operational functions and to supply chain imperatives. Longer-term strategic and structural shift towards adaptability (along with other goals) is the hallmark of “adaptability,” explained by Kamalahmadi and Parast (2016). Ponomarov and Holcomb (2009) define resiliency as an entity’s capacity to continue to function and operate while absorbing external shocks. Agile speaks of decisiveness in change versatility, while technologically supersedes shift adaptive accelerates responsive purposiveness access in the space of Core, the goals of visibility are instant. Muhammad et al., 2025, Narayanan et al, 2024 (a, b) highlight the tech-centered propelling empowerment of real-time tracking of all supply components of the chain and suggest its aiding toward on-the-spot decision making, enabling instant solutions toward resolution acceleration.

The use of Digital Twin technology in modern-day supply chains can markedly improve their resiliency and operational efficiency. Each Digital Twin acts as a unique responsive virtual replica of a physical unit, integrating real-time information and simulations to render insight-based action (Fuller et al., 2020). Each Digital Twin embeds virtual checkpoints that validate in real-time, evaluate future states and compute alternative scenarios. According to Negri et al. (2017), the virtual model stays aligned and synchronized with the physical model ‘twin’ via streaming data. Digital Twin technology, when combined with predictive analytics, strengthens a company’s ability to proactively manage potential disruptions and assess a range of counteraction plans (Qi & Tao, 2018). A clear and visual representation of the supply chain under different configurations and environments can be created through scenario-based modelling which turns insights into visual scenarios. Comprehensive simulation as described by Barricelli et al. (2019), captures a vast range of scenarios, ensuring that the best-informed decision is made. The improvements garnered in the logistics and manufacturing sectors in the supply chain, considering the context, are super operational performance, reduced risks, and profound enhancement (Caridi et al., 2014; Liu et al., 2020).

The excitement surrounding digital twins (DTs) is palpable given their capabilities pertaining to visibility, operations, and risk management in the supply chain sector. With DTs, tactical and strategic decision-makers have the option to execute preventative measures on supply chain disruptions and bottleneck scenarios far in advance of their escalation (Boschert & Rosen, 2016). Further, DTs are critical to risk management, specifically in modelling and analyzing potentially disruptive scenarios, thus allowing a chain to devise, simulate, and optimize strategies for unanticipated disruptions far in advance (Kritzinger et al., 2018). Beyond risk management, DTs focus on operational data to enhance performance by correcting actions at the underperforming nodes, thus reducing costs and improving service levels (Tao et al., 2018). There is a consensus on the theoretical promise of DTs, but case studies on their application in specific supply chain contexts are absent (Ivanov et al., 2020). These studies, which focus on DTs in a vacuum, seem to overlook solving practical problems and the multidomain integration challenges (Verdouw et al., 2021).

Regardless of the opportunities presented by the development of digital twin technologies, there exists a considerable gap within the literature concerning these technologies and their potential use towards improving the supply chain’s resilience. In particular, there is a gap within the literature that creates an in-depth foundational analysis that applies digital twin technologies towards significantly improving the resilience within bounded, dynamically interlinked global supply chains (Jones et al. 2020). Čalić & Dolgui (2020) pointed out the lack of interdisciplinary empirical research that would illustrate the possible resilience enhancement offered by digital twin technology within different sectors. Moreover, the lack of certainty with respect to data interoperability, the incorporation of new twins into legacy systems, and the high recurring costs have created substantial gaps within the research (Zhang et al., 2019). To fully exploit the potential of technology in the intentional development of supply chains that are able to withstand and rapidly rebound from disruptions, these areas of research need to be addressed.

As you develop the conceptual framework, use it to evaluate the phenomenon in light of several important theories. Within this context, digital twins (DTs) showcase the Resource-Based View (RBV) theory, which posits that firms achieve sustainable competitive advantage by uniquely leveraging valuable, difficult-to-obtain, and hard-to-duplicate resources. Complexity Theory adds to the inquiry by considering the supply chains as adaptive systems that change their structure over time in response to perturbations; thus, the findings from

the DH serve as empirical confirmation for the complexity phenomenon. DTs, because of their ability to virtualize and spatially analyze intricate systems, afford specific tools for navigating through the intricate dependencies articulated by complexity theory. Further, systems theory adds to this view through its emphasis on integration and interdependence; by providing the means for real-time observation and control of the myriad interdependent activities that form a supply chain, DTs give systems theory empirical validation. Altogether, the outlined theories offer a coherent answer to how DTs might enhance supply chain resilience to perturbations.

Table 1: Literature Review Matrix: Digital Twin (DT) and Supply Chain Resilience

Author(s) & Year	Focus Area	Key Findings	Theoretical Lens	Relevance to DT
Ali et al. (2020)	ERP Implementation	ERP systems improve supply chain visibility and integration.	Information Systems Perspective	Supports foundational IT infrastructure for DTs.
Handra & Sundram (2023)	HRIS & AI in Defense	AI and HRIS improve operational efficiency.	Digital Transformation	Highlights the impact of AI in digitized systems.
Ibrahim et al. (2017)	Green Logistics Practices	Adoption of green practices enhances sustainability.	Sustainability Framework	Green practices align with DT-enabled optimizations.
Mkumbo et al. (2019)	Performance Measurement in SCM	Integrated practices improve firm performance.	SC Performance Models	Measurement systems can be enhanced through DTs.
Muhammad et al. (2025)	Citizenship & Sustainability	SC Good citizenship supports resilient SCs.	CSR & Sustainability	DTs can support transparency in SC citizenship efforts.
Narayanan et al. (2024a)	Palm Oil Sustainability	SC Certification and awareness improve consumer trust.	Consumer Behavior	DTs enable traceability of certified goods.
Narayanan et al. (2024b)	SC Finance & Working Capital	Multi-dimensional strategies optimize capital.	Finance Operations	DTs support financial visibility and forecasting.
Sivan et al. (2024a)	Safety Construction SCs	Integrated practices in safety drive sustainability.	Risk Management	DTs can monitor real-time safety compliance.
Sivan et al. (2024b)	Safety Culture Logistics	in Perception surveys guide improvement strategies.	Organizational Behavior	DTs offer platforms for tracking cultural indicators.
Sureshkumar et al. (2024)	AI-Powered Assessment	Risk AI enhances proactive risk control.	AI and Management	Risk Direct integration with DT risk modules.
Wong Chee et al. (2024)	Palm Oil SC Strategy (SWOT-QSPM)	Strategic alignment enhances performance.	Strategic Management	DTs support scenario simulation in SWOT analysis.

The literature review matrix synthesizes critical scholarly contributions on Digital Twin (DT) Technology and its impact on supply chain resilience. Handra and Sundram (2023), as well as Ali et al. (2020), define ERP, Human Resource Information Systems, and Artificial Intelligence as relevant and prerequisite foundational layers, which, if implemented, allow for efficient Digital Twin Technology utilization. Ibrahim et al. (2017) and Muhammad et al. (2025) shift the focus toward sustainability and nationalism, claiming that DTs enhance transparency and process accountability. Narayanan et al. (2024a, c) add to this discussion by integrating consumer trust, financial sustainability, and digital maturity as components of DT-enabled operational effectiveness, explaining also how traceability, predictive analytics and performance dashboards enhance operational effectiveness. Sivan et al. (2024a, 2024b) concentrate on safety culture, exploring DTs live-monitoring and behavior-tracking functionalities and how these reinforce stringent safety compliance. The

anticipatory risk landscape coupled with forecast-calculated strategy is explored by Sureshkumar et al. (2024) and Wong Chee et al. (2024), who contend together that DTs tend to transform complex supply network architectures to be more agile, flexible, and resilient.

3. Methodology

In developing a strategic Digital Twin (DT) application for supply chain resilience, we pursued a stepwise, integrative methodology that yielded a robust conceptual framework. Its design synthesizes, on the one hand, unexplored theoretical assertions distilled from existing literature, and, on the other, empirically grounded perspectives provided by seasoned industry practitioners whose views were cross-queried with scholarly peers. The foundation stage involved a sweeping review focused on DTs, resilience paradigms, and paradigmatic shifts induced by digital transformation. Prior work, including Kamble et al. (2021), had duly noted a DT's capacity to enhance end-to-end visibility, empower anticipatory analytics, and harmonize workflow efficiency. Nonetheless, the survey especially registered misaligned, siloed constructs and an essential absence of an integrative schema that marries DT capabilities to supply chain-endurance objectives. Complementing these literary discontinuities, we engaged Socio-Technical Systems Theory and the Actor-Network Theory, tracing back to Latour's 2005 explications, to interrogate the dynamic dialectic between digital artefacts and human agency within multiscalar supply chain networks (Bostrom & Heinen, 1977). The synthesised theoretical insights guided the framework's assembly by clarifying the interaction topology and guiding structural partitioning within the proposed architecture.

The modern-day unpredictable natural calamities, political calamities, and pandemics serve as stressors toward a business's continual function (Mkumbo et al., 2019). These issues have instigated a shift toward comprehensive study centered around a business's Supply chain and how resilient its systems and processes are, keeping core functions uninterrupted and operative (Handra and Sundram, 2023). Supply chain resilience refers to a system's overall ability to prepare, adjust, and recover proactively while Agile, adaptive, proactive, and reactive core functions remain unhampered, uninterrupted, and undisturbed while supporting core functions uninterrupted. Resilience encompasses four core themes namely agility, adaptability, robustness, and visibility. "Agility" (Dubey et al., 2019) speaks toward the system's ability to refractor and operationally shift to realign to set operational functions and to supply chain imperatives. Longer-term strategic and structural shift towards adaptability (along with other goals) is the hallmark of "adaptability," explained by Kamalahmadi and Parast (2016). Ponomarov and Holcomb (2009) define resiliency as an entity's capacity to continue to function and operate while absorbing external shocks. Agile speaks of decisiveness in change versatility, while technologically supersedes shift adaptive accelerates responsive purposiveness access in the space of Core, the goals of visibility are instant. Muhammad et al., 2025, Narayanan et al, 2024 (a, b) highlight the tech-centered propelling empowerment of real-time tracking of all supply components of the chain and suggest its aiding toward on-the-spot decision making, enabling instant solutions toward resolution acceleration.

The application of Digital Twin technology in modern supply chains can greatly improve their resilience and efficiency. Every Digital Twin acts as a dynamic virtual replica of a physical asset, incorporating real-time data and simulations to generate insights that can be acted upon (Fuller et al., 2020). Digital Twins incorporate virtual checkpoints that, in real time, validate, generate forecasts, and compute alternative scenarios. As Negri et al. (2017) explain, "the virtual model remains aligned and synchronized with the physical twin" through streaming data. Digital Twins, combined with predictive analytics, empower companies to identify possible disruptions and assess a number of pre-emptive mitigation strategies (Qi & Tao, 2018). Such insights can be rendered graphically through scenario-based modelling, which captures different configurations and environments of the supply chain, offering a clear visual representation. A comprehensive simulation that captures a wide range of scenarios is critical, as it maximizes the information available to ensure that the best decision is made, as noted by Barricelli et al. (2019). The improvements Digital Twins offer in Logistics, Manufacturing, and the Supply Chain result in super operational performance and reduced risk (Caridi et al., 2014; Liu et al., 2020).

The enthusiasm revolves around the supply chain industry's operational risk management and process refinement with the implementation of digital twins (DTs). Tactical and strategic decision makers can mitigate supply chain disruptions and bottlenecks with DTs long before they materialize (Boschert & Rosen, 2016).

Furthermore, DTs are crucial in risk management because they model and analyze disruptive scenarios, allowing supply chains to create and optimize simulations of contingent strategies for calculated strategies regarding future disruptions (Kritzinger et al., 2018). Besides risk management, DTs focus on improving performance metrics by overhauling the corrective action processes in the deficient nodes, which reduces operational costs and enhances the overall service level (Tao et al., 2018). There is an overarching consensus on the theoretical promise of DTs, but there is a notable absence of empirical research investigating the practical application of DTs in specific supply chain contexts (Ivanov et al., 2020). These studies seem to overlook the integration across multiple sectors as they focus on the concept of DTs (Verdouw et al., 2021).

Noted gaps in the literature focus on the use of digital twin technologies to improve the resilience of Supply Chains, which is especially concerning given how promising this technology is. Specifically, it is difficult to find literature that deals specifically with the development of foundational frameworks that incorporate digital twin technologies within bounded, dynamically interlinked global supply chains that increase resilience (Jones et al., 2020). Čalić & Dolgui (2020) emphasized the absence of empirical cross-sectoral studies demonstrating the prospective resilience advantages of digital twins within single industries. Furthermore, the gap between the expected and published studies concerning digital twins is also fuelled by insufficiently defined data interdependence, the merging of new twins with the existing twin, and the overall high costs of digital twins (Zhang et al., 2019). Bridging these gaps is crucial to intentionally designing supply chains that are able to withstand and rapidly bounce back from unpredictable disruptions.

The conceptual framework should guide the examination of the phenomenon through the lens of certain theories. The Resource-Based View (RBV) highlights the notion that firms achieve a sustainable competitive advantage through a unique and valuable harnessing of resources that are difficult to obtain and replicate; this most certainly applies to digital twins (DTs). Complexity theory broadens the inquiry by regarding supply chains as adaptive systems that alter their structural configuration continuously over time in response to perturbations; thus, the DH findings serve as the empirical evidence of the complexity phenomenon. Through their ability to virtualize and analytically dissect intricate networks, DTs grant the tools necessary to manoeuvre through the elaborate interdependencies described by complexity theory. Furthermore, systems theory supports this notion by emphasizing integration and interdependence; by providing real-time observation and control of countless interdependent activities that make up a supply chain, DTs aid systems theory. Each of these theories, combined, forms a coherent response to the question of how DTs could enhance the resilience of supply chains to perturbations.

4. Conceptual Framework

The provided framework seeks to explain the role of Digital Twin (DT) technology in the enhancement of supply chain resilience by integrating three core dimensions: inputs, processes, and outcomes. These components describe how DTs engage with supply chain systems to bolster resilience. There is a visual representation of the framework, which shows the interconnections of these dimensions.

Table 2: Specific Variable Names for Conceptual Framework

Variable Type	Specific Variable Name	Description
Independent	Digital Technology Enablers	Includes IoT devices, artificial intelligence, real-time data streams, and simulation tools that enable digital twin functionality.
Mediating	Digital Twin Operational Functions	Encompasses key DT processes such as demand forecasting, risk assessment, scenario planning, and monitoring.
Dependent	Supply Chain Resilience Capabilities	Represents the resilience outcomes, including responsiveness, flexibility, risk mitigation, and robustness.

This given explanation offers a detailed overview of the interactions among the variables within the given scope

of the conceptual framework while maintaining the relationships and interdependencies sufficiently clear.

Digital Technology Enablers

This research looks at the entire supply chain integration of the digital twin tools. Their focus is on the subsystems of analytic AI, including sensor networks, real-time data processing, and complex scenario simulators. Propagating the operational state of machinery, vehicles, and inventory systems is achieved through the Internet of Things (IoT) technologies. Xu et al. (2021) called this a version of waking and responsive visibility. Systems are now being designed with AI capabilities that expand beyond the ability to simply respond to stimuli and into proactive order fulfilment, prescient maintenance, and supply bottleneck anticipatory role execution (Jahangirian et al., 2022). To maintain uninterrupted processing of supply chains, both real and ideal, streams of data are ingested without interruption to ensure perpetual optimization. The task of processing the streams is real-time, and the streams themselves are infused with advanced causal impact analysis (Lee et al., 2020). Systems are also capable of adaptive resilient strategy reconstruction, where flexible strategy reconstruction is achieved through quantified resilience, permitting the modelling of recovery strategy computation across vast configuration simulation arrays with detailed optimal plan extrapolation. The use of digital twin technologies facilitates direct interventions, which enable systems to perform autonomous logistics and production through computation of optimal recovery strategy, virtual resilience experimentation, and reconstruction of flexible recovery strategies.

Digital Twin Operational Functions

The use of digital twins in core supply chain processes like risk assessment, forecasting, and planning happens within specific boundaries. Monitoring inventory levels and tracking in real-time sharpens accuracy, thus tighter synchronization of production schedules is possible (Singh et al., 2022). Strengthening risk assessment with real-time dynamic supply chain mapping of weaknesses and calculating the likelihood of certain disruptive events improves forecasting accuracy (Ivanov et al., 2021). The scenario analysis is performed faster due to simulation engines within the twin that allow for quick projection of strategic outcomes and the most resilient risk-mitigation pathways in evasive twin tunnelling (Barricelli et al., 2019). The described digital twin technologies have significantly transformed and improved the situational awareness and responsiveness of adaptive supply chains.

Supply Chain Resilience Capabilities

The focus on measuring supply chain resilience has recently been sparked by the capabilities afforded by digital twins (DTs). Perhaps the most welcomed benefits conferred include heightened responsiveness, operational flexibility, and superior risk shielding. The responsiveness DTs bestow upon the supply chain is operational visibility, and demand or supply sensing communications (Min and Zhou, 2020). Flexibility improves as DTs mitigate and counterbalance disruptions to processes by remixing processes and resource allocation to restore flow and replenish processes (Kamble et al., 2021). Risk shielding, as explained by Verdouw et al. (2021), is reinforced risk shielding as DTs perform pre-emptive analytics and forecasting. Poor forecasting and analytics identify weak points many steps before costly interruptions stand a chance to occur. The aggregate of these benefits underscores the risks averted through DTs and the capacity to transform supply chains into resilient systems that withstand and endure shocks, emerging as stronger systems.

The framework is further enhanced with the following hypotheses.

- DT technology adoption through the IoT and AI increases the visibility of supply chain activities in real-time.
- DT technology implemented in the supply chain featuring advanced capabilities for risk and scenario versatile planning improves supply chain responsiveness and flexibility.
- The use of DT technology improves resilience and diminishes the impact of disruptions on supply chains.

This framework provides the means both conceptually and empirically to analyze the impact of DTs on the enhancement of supply chain resilience.

Discussion

This review develops a framework for assessing the impact of Digital Twin technology upon resilience in a supply chain. This framework encompasses technology enablers and processes and their corresponding resilience outcomes, fulfilling a systematic analytical purpose for both practitioners and scholars who aim to utilize Digital Twins. The next section outlines the model's initial theoretical implications, and afterward, it shifts to practical implications, focusing first on barriers to adoption and subsequently outlining avenues for future research.

Theoretical Contributions

This framework contributes to the literature with respect to the intersection of digital transformation and the resilience of the supply chain. One area of research focus often tends to ignore other relevant areas. In this case, the literature is overly compartmentalized, and this is the gap that this study is trying to address by formulating a cohesive framework using various disparate elements. The framework incorporates drivers such as IoT, AI, and simulation technologies, which aid in understanding the effects of these contemporary tools on the supply chain in greater depth. It is anchored on the socio-technical systems theory, which emphasizes the interplay of technology and human action regarding the employment of complex supply chains (Bostrom & Heinen, 1977). In addition, this framework contributes to the literature on digital resilience by pinpointing certain mediating factors—essentially, real-time monitoring and scenario-based planning—resiliency metrics that are monitored in real time and, in effect, anchor resilience metrics. Likewise, it augments the framework and expands the theoretical discussion by integrating digital technologies into the Resource-Based View, articulating how these technologies become distinctive strategic assets that bestow enduring competitive advantage (Barney et al., 2021).

Practical Implications

This guideline can aid supply chain managers by showing them how to more effectively incorporate digital twin technology to achieve heightened supply chain resilience. With focused attention to monitoring in real time and making accurate forecasts, proactive action can be taken to avert major disruptions. For instance, IoT sensors provide real-time data that reveals errors, bottlenecks, or even the health of the equipment before they become widespread (Tiwari et al., 2022). In parallel, scenario planning through simulations provides decision makers a virtual sandbox to rehearse a gamut of responses to myriad risks, thus improving decision-making in real-life emergencies. Adherence to the guideline strengthens the argument that technology in isolation with no investment in staff training will produce no value and inordinate funds will be rendered as other organizational resources will not be utilized. Adoption of this structured approach increases organizational agility by enabling companies to respond swiftly and smoothly to shifting conditions, thus preserving optimized operations during unpredictable change.

Challenges in Adopting DT Technology

The use of digitized twins in supply chains poses many challenges, one of the most acute being the monetarily-straining sensors, simulation ecosystems, and AI systems (Narayanan et al., 2024a). The lack of qualified engineers exacerbates the issue. Logistics networks that are more conservative in their approaches are, in part, a reaction to the need to safeguard intellectual capital. Supply chains are a treasure trove of proprietary data. Any operational infringement could compromise critical business processes, which would be devastating to a firm's reputation. These breaches are vital for firms to avoid and, thus, supply chains are managed with a very conservative orientation. The challenges posed by the coexistence of legacy systems are no less daunting. These legacy systems have persisted for decades, and due to the novelty of digitized twins, there is a risk of silos if the enhanced systems are unable to interface and collaborate. This is the opposite of the vision of a digitized holistic multiverse (Sundram et al., 2025; Sundram et al., 2018). Such challenges illustrate the relentless supply chain digitization competition.

Future Trends

Future evolution of digital twin technology in supply chains will be driven by tighter integration with other Industry 4.0 pillars, notably blockchain, 5G, and machine learning. Saberi and colleagues (2019) demonstrated that blockchain-derived traceability and security bolster the parallel, continuous data streams that digital twins require. With 5G, the practical benefits expand: improved bandwidth and latency translate into tighter simulation loops and real-time adjustments (Sharma et al., 2021). Meanwhile, continuous enhancements in

machine learning—from anomaly detection to demand sensing—will yield sharper, more granular risk and opportunity assessments. Collectively, these base technologies will reduce the dependence on human data entry and decision-making, moving more processes into closed, self-running loops. A parallel thread worth mentioning is the emergence of digital twins in circular supply chains, where they serve to optimize resource loops and minimize waste (Genovese et al., 2022). We synthesize these observations into a structured conceptual framework that clarifies how digital twins can fortify supply chain resilience. By marrying theoretical constructs with empirical implementation, the framework serves both scholars seeking to advance the literature and practitioners tasked with operational application. Even though challenges such as expense, required expertise, and data protection persist, the continued advancement of Industry 4.0 technologies shows considerable promise. Existing studies indicate that an expanding pool of empirical evidence and ongoing innovation can contribute to more robust and adaptable supply chains Rasi et al., 2022; Razak, Othman, & Sundram, 2015; Selvarajah et al., 2025.

5. Conclusion

The ever-changing global interconnected disruptions along with the intricate configuration of the global supply chain necessitate resilience embedded equally across every operation (Narayanan et al., 2024b; Narayanan et al., 2025). As DT technologies are applied, their fulfillment requirements are still approached. As described in Kristoffersen et al. (2021), DTs enable predictive modelling and scenario simulation which provide 360-degree visibility. This ability of DTs aids in supply chain processes control and enables the pre-emptive adjustment, impact mitigation, and controlled recovery of the processes. These capabilities attest to the realization of constructing agile supply chains capable of enduring and absorbing disruptions while sustaining operations with minimal delays (Delic and Eyers, 2020). The developed conceptual framework enriches the academic discourse by describing theoretical gaps and investigating how DTs impart resilience. This framework contributes to the emerging frontier of DT technology and aims to integrate theoretical and empirical gaps that are grounded in contemporary innovations with timeless practical frameworks.

Based on the work of Singh et al (2021), businesses can achieve sustainable competitive advantage through the use of digital technologies with the help of an emerging technologies integration framework that employs specific resilience strategies. In my view, this framework fills an important gap in the literature by integrating technological capabilities with resilience factors, thus moving the conversation on the supply chain transformation technology (Müller et al., 2021). To the best of my knowledge, no one has empirically tested the framework so far. That said, it is important to note that assessing it within the context of real-world impact and value would require empirical work. We extend the invitation to researchers from all fields to apply the framework in diverse industrial and geopolitical settings in order to broaden its relevance and applicability. Digital technology's impact on demand sensing and risk aversion could be studied with mixed-method frameworks that use rich qualitative case studies and extensive quantitative data (Tortorella & Fettermann, 2018). Concurrently, such studies could evaluate how digitally transformative strategies applied in an interventionist manner strengthen resilience metrics over time. Such studies would strengthen the understanding of how technology enhances supply chain resilience and identify additional avenues for enhancement.

With regard to supply chains, the integration of digital technologies introduces issues such as interoperability, scalability, and concerns related to digital twin technologies. Concerning the digital twin application in supply chains, the frameworks pose the challenge of how their dynamic, evolving, and interdependent systems model relates to the legacy systems and processes in place. Further research could focus on telemetry frameworks, which digitally model shapes as metrics of active spatial geometry that would digitally embed telemetry concerning corporate teamwork alignment metrics. Apart from those efforts, scalability research could investigate the operation of digital twins in complex multi-tiered networks, including their application in supply chains with geographically disparate constituents and the enhancement of efficacy in multi-tiered networks.

What and how supply chains foresee, analyze, react to, and recover from disruptions is determined by the modelling and forecasting of complex systems with digital twins. Outcomes from corporate digital readiness and the firm's technology, operational practice, and corporate resilience become the focus in assessing the

interdependence between these variables. Emphasizing integrated empirical scaling validation while resolving scaling challenges should harness more value with the application of digital twins and optimization in supply chain management. The development of a sustainable economy is anchored on digital twin technology that enhances the critical functions of the supply chain, simultaneously fostering resilience.

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