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The Role of Digital Twin Technology in Enhancing Supply Chain Resilience and Predictive Risk Management

Faiq Ali Khan[1], Dr. Shankar Subramanian Iyer[2]

[1]DBA Researcher at Westford University College, Al Khan, Sharjah, UAE

[2]Faculty, Westford University College, Al Khan, Sharjah, Orcid no: https://orcid.org/0000-0003-0598-9543

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Corresponding Author:
Dr. Shankar Subramanian Iyer

ABSTRACT

The increasing complexity and vulnerability of global supply chains have amplified the need for technologies that enable agility, foresight, and resilience. Amid ongoing disruptions driven by pandemics, geopolitical uncertainty, and climate events, Digital Twin Technology (DTT) has emerged as a transformative solution. While extensively explored in the engineering and manufacturing sectors, its application in supply chain management—particularly its influence on resilience, predictive risk management, operational efficiency, and visibility—remains under-researched. This study addresses this gap by exploring how DTT adoption influences these critical dimensions of supply chain performance. Using a qualitative research design, this study employed semi-structured interviews with 15 supply chain and technology professionals across diverse sectors. The participants were selected based on their experience with digital transformation and risk mitigation in supply chain settings. The collected data was analysed through thematic analysis, allowing the identification of recurring patterns and the construction of thematic categories that reflect the role of DTT in enhancing various supply chain outcomes. The analysis revealed five core themes directly aligned with the proposed conceptual model: Real-Time Data Integration Enhancing Visibility, Simulation and Scenario Planning Driving Risk Management, Organizational Readiness and System Interoperability Influencing Operational Efficiency, Predictive Analytics Enabling Faster Disruption Response, and Strategic Agility Facilitating Supply Chain Resilience. The findings support the conceptual pathway in which DTT, characterized by real-time integration, simulation capabilities, and predictive analytics, significantly contributes to improved supply chain resilience, more effective predictive risk management, increased operational efficiency, and enhanced end-to-end visibility. However, barriers such as data interoperability, high implementation costs, and limited digital capabilities among SMEs were also reported. This study makes a theoretical contribution by empirically validating the multi-dimensional impact of Digital Twin Technology as an independent variable influencing four core dependent dimensions of supply chain performance: resilience, predictive risk management, operational efficiency, and visibility. The findings affirm that DTT enables firms not only to react to disruptions but also to anticipate and simulate potential risks, thus reinforcing a proactive and data-driven supply chain strategy. These insights are particularly relevant for policymakers and business leaders aiming to strengthen supply chain infrastructures in volatile environments. The research also highlights the importance of strategic alignment, technological maturity, and investment in digital capabilities to fully leverage the transformative potential of digital twins.

KEYWORDS: Digital Twin Technology; Supply Chain Resilience; Predictive Risk Management; Operational Efficiency; Supply Chain Visibility; Thematic Analysis; Real-Time Simulation; Scenario Planning; Organizational Readiness; Qualitative Research

INTRODUCTION AND BACKGROUND

In recent years, the global supply chain landscape has become increasingly complex, vulnerable, and unpredictable. The rise of globalization, rapid digitization, fluctuating consumer demand, and mounting environmental uncertainties have brought about unprecedented challenges for supply chain professionals. Events such as the COVID-19 pandemic, geopolitical disruptions like the Russia-Ukraine war, semiconductor shortages, port congestions, and climate-induced disasters have exposed the fragility of traditional supply chains and highlighted the urgent need for resilience, agility, and predictive risk management. In this context, Digital Twin Technology (DTT) has emerged as a groundbreaking innovation capable of transforming how supply chains operate, adapt, and recover. A digital twin is a real-time virtual representation of a physical system, process, or asset, enriched with data streams from sensors, analytics platforms, and artificial intelligence. When applied to supply chains, digital twins enable organizations to simulate logistics flows, visualize operations across multiple tiers, anticipate disruptions, and test strategic decisions in a risk-free environment. By offering a continuous loop of data collection, modelling, prediction, and feedback, DTT supports real-time decision-making and enhances an organization's ability to prepare for and respond to supply chain shocks. Despite its growing popularity in sectors such as aerospace, automotive, and manufacturing, the application of digital twin technology in supply chain management remains underexplored in academic research (Guo et al., 2024). Most existing literature focuses on the technological architecture of digital twins or their use in product lifecycle management, leaving a critical gap in understanding their strategic value in enhancing supply chain resilience, predictive risk management, operational efficiency, and visibility. This research aims to bridge that gap by examining how DTT adoption influences these key outcomes from the perspective of supply chain practitioners. The primary purpose of this study is to investigate the role of digital twin technology in enabling supply chains to be more resilient and risk aware. Using qualitative methods, the study seeks to provide empirical insights into the experiences of supply chain professionals who are leveraging DTT in real-world settings. In particular, the study explores how various features of digital twins—such as real-time data integration, virtual simulation, system interoperability, and predictive analytics—translate into tangible improvements in disruption response, risk mitigation, process optimization, and supply chain visibility (Singh, 2025).

Current Trends and Usefulness

The ongoing evolution of Industry 4.0 and the widespread adoption of the Internet of Things (IoT) have significantly accelerated the integration of digital technologies across global supply chains. Among these, Digital Twin Technology (DTT) has emerged as a central enabler, offering organizations an innovative way to monitor, simulate, and optimize supply chain operations. Digital twins are increasingly being recognized for their ability to facilitate end-to-end visibility by creating real-time virtual representations of the entire supply chain—from suppliers and manufacturers to distributors and customers. They also support predictive risk management by enabling simulations of potential disruptions such as supplier failures, transportation delays, or demand surges, allowing businesses to anticipate and proactively mitigate risks. Furthermore, DTT enhances operational efficiency by supporting dynamic modelling, real-time decision-making, and process optimization, thereby reducing costs and improving responsiveness. It enables robust scenario planning and contingency testing without the need to interfere with ongoing operations, which is particularly beneficial in times of uncertainty or strategic change (Jariwala, 2024). Additionally, digital twins contribute to sustainability and waste reduction by identifying process inefficiencies, optimizing resource utilization, and minimizing energy consumption and material waste. Real-world applications of digital twins are increasingly evident across industries. In logistics and retail, companies like Amazon and DHL are leveraging digital twins to simulate last-mile delivery networks and warehouse operations, improving delivery speed and inventory accuracy. In the manufacturing sector, Unilever has deployed digital twins in its plants to enhance energy efficiency and reduce equipment downtime. Similarly, in the automotive industry, BMW uses digital twin models to simulate factory layouts and streamline production planning, thereby improving throughput and spatial efficiency. These examples underscore the growing recognition of digital twins as a strategic asset in modern supply chain management (Rahmani et al., 2024).

Challenges Faced

Despite the transformative potential of Digital Twin Technology (DTT), many organizations face significant challenges when attempting to adopt and scale its use within supply chain environments. One of the most pressing barriers is the high implementation cost associated with developing and deploying digital twin systems. These costs include not only the acquisition of advanced sensors, software platforms, and infrastructure but also the expenses related to training, system maintenance, and ongoing upgrades. Compounding this issue is the often-unclear return on investment (ROI)—especially in the early stages of adoption—making it difficult for decision-makers to justify the financial outlay without clear and immediate performance metrics. Another major hurdle is the complexity involved in integrating diverse data sources and legacy systems across the supply chain. Many organizations operate with outdated IT infrastructures and siloed data environments, which pose compatibility issues when trying to feed real-time data into digital twin platforms (Tripathi et al., 2024). Effective implementation of DTT requires seamless interoperability between various technologies such as IoT devices, ERP systems, and AI-driven analytics, which is often easier said than done. These integration issues not only delay deployment but can also limit the effectiveness of digital twins in providing real-time, actionable insights. The shortage of digital skills and analytical capabilities among supply chain teams further impedes adoption. Building and managing digital twin environments requires expertise in data science, systems modelling, machine learning, and process engineering—competencies that are often lacking in traditional supply chain roles. Organizations must either invest heavily in upskilling their current workforce or compete in a tight labour market to attract specialized talent, both of which can be resource intensive. Data privacy and cybersecurity concerns also present significant challenges, particularly in complex, multi-tier supply chains where data is shared across multiple stakeholders. The real-time nature of digital twins means continuous data exchange, which increases exposure to cyber threats and the potential misuse of sensitive information. Ensuring compliance with data protection regulations such as GDPR, and establishing secure, encrypted data environments are essential but can be technically and administratively burdensome. Moreover, there is a lack of standardized frameworks and governance models for digital twin implementation (De Azambuja et al., 2024). Without clear industry standards or regulatory guidelines, organizations often struggle with best practices around design, deployment, and evaluation of digital twin initiatives. This absence of common protocols creates inconsistency in implementation approaches and hinders collaborative development across industry ecosystems. Adding to these practical challenges is a widespread misconception that digital twin technology is only suitable for large corporations or manufacturing-intensive sectors. This myth has significantly limited adoption among small and medium-sized enterprises (SMEs) and service-driven supply chains, many of which could benefit from enhanced visibility and agility just as much as their larger counterparts. The perception that DTT is too complex, costly, or irrelevant for smaller organizations discourages investment and innovation at lower tiers of the supply chain, where resilience and predictive capabilities are equally critical. While the advantages of digital twin technology are compelling, its widespread implementation is hindered by financial, technical, human resource, and regulatory challenges. Addressing these barriers will require not only strategic investments and leadership commitment but also ecosystem-wide collaboration, policy support, and greater awareness to dispel myths and democratize access to this powerful innovation (Mazzetto, 2024).

This study is significant for both academia and industry. From a scholarly perspective, it contributes to the underdeveloped body of knowledge linking digital twin capabilities to specific supply chain performance outcomes such as resilience, predictive risk management, operational efficiency, and visibility. For practitioners, it provides actionable insights into the strategic value, practical challenges, and success factors associated with digital twin deployment. It also offers guidance for policymakers and digital transformation leaders on how to build future-proof supply chain ecosystems that are not only reactive but proactive and predictive. Digital Twin Technology is not just a digital upgrade, it is a strategic imperative for resilient, intelligent, and agile supply chains. This study lays the foundation for a deeper exploration of how DTT can be a critical enabler of sustainable competitive advantage in an era of constant disruption (Hossain et al., 2024).

Research Scope

This research focuses on exploring the strategic role of Digital Twin Technology (DTT) in enhancing critical aspects of supply chain performance—specifically supply chain resilience, predictive risk management, operational efficiency, and supply chain visibility. The study is qualitative in nature and investigates the experiences, perceptions, and insights of professionals who are actively involved in digital transformation and supply chain operations. The scope encompasses medium to large enterprises across various industries, including manufacturing, logistics, retail, and distribution, where digital twin technologies are being piloted or implemented. The research does not aim to evaluate the technical architecture or software design of digital twins; rather, it seeks to understand their practical application, strategic value, and challenges from a managerial and operational standpoint. It is limited to supply chains that are undergoing or have undergone digital transformation initiatives and includes participants from both developed and emerging market contexts. The study also considers organizational and technological readiness, cultural and infrastructural barriers, and the enabling role of leadership in the adoption and scaling of digital twins.

Research Questions

1. How does Digital Twin Technology influence supply chain resilience in the face of disruptions and uncertainties?
2. What role does Digital Twin Technology play in enhancing predictive risk management capabilities within supply chains?
3. To what extent does Digital Twin Technology improve operational efficiency across various supply chain functions?
4. How does the implementation of Digital Twin Technology enhance visibility and transparency throughout the supply chain network?

Research Objectives

1. To explore the impact of Digital Twin Technology on strengthening supply chain resilience through faster response and recovery mechanisms.
2. To examine how digital twin-enabled systems contribute to predictive risk identification, scenario analysis, and proactive decision-making in supply chains.
3. To assess the role of Digital Twin Technology in improving operational efficiency, including process optimization, lead time reduction, and resource utilization.

4. To investigate how digital twin adoption enhances supply chain visibility by enabling real-time monitoring and end-to-end data integration across supply chain tiers.

LITERATURE REVIEW

The adoption of Digital Twin Technology (DTT) in supply chain management has become increasingly relevant in the wake of global disruptions and heightened operational uncertainties. Rooted in the principles of cyber-physical integration, DTT enables real-time data exchange, virtual simulation, and predictive analytics—tools that organizations can leverage to enhance decision-making, resilience, and efficiency across the supply chain. However, academic inquiry into how specific supply chain dimensions influence DTT adoption remains underdeveloped. This literature review critically explores the four core constructs—Supply Chain Resilience, Predictive Risk Management, Operational Efficiency, and Supply Chain Visibility and their theoretical connection to digital twin adoption (Lyytinen et al., 2024).

Supply Chain Resilience

Supply chain resilience is defined as the ability of a supply network to anticipate, prepare for, respond to, and recover from disruptions. It encompasses dimensions such as response time to disruption, recovery time, operational flexibility, supplier adaptability, and inventory buffering. With increasing exposure to external shocks, firms must develop systems that are not only robust but also adaptable. According to Dynamic Capabilities Theory (DCT), resilience reflects a firm's ability to transform and reconfigure resources in response to uncertainty. Digital Twin Technology acts as an enabler by simulating disruption scenarios, optimizing recovery pathways, and reconfiguring resources (Ogunsoto et al., 2025). For instance, DTT can model the impact of port closures or supplier failures and help determine alternative sourcing strategies. Thus, the literature supports the notion that supply chain resilience significantly influences DTT adoption, forming the basis of Hypothesis 1 (H1).

Predictive Risk Management

Predictive risk management refers to a firm's capability to identify, analyze, and mitigate potential risks before they materialize. This involves risk identification accuracy, forecasting capabilities, scenario planning efficiency, real-time risk monitoring, and decision-making speed. The integration of DTT facilitates predictive risk management by allowing organizations to anticipate events through real-time data analytics and advanced simulations. This aligns with DCT's sensing and seizing functions, enabling firms to detect environmental threats early and implement timely responses. Furthermore, under Contingency Theory, the extent to which DTT enhances risk management is dependent on organizational context—such as industry type, digital maturity, and data infrastructure. While existing studies have emphasized DTT's role in safety monitoring and process optimization (Patil et al., 2024), few have explored its strategic use in predictive supply chain risk governance. This justifies Hypothesis 2 (H2), proposing a significant relationship between predictive risk management and DTT adoption.

Operational Efficiency

Operational efficiency refers to the ability of an organization to deliver goods and services in a cost-effective, timely, and resource-optimized manner. Key sub-variables include lead time reduction, forecast accuracy, cost minimization, asset utilization, and resource allocation. From the Resource-Based View (RBV), DTT represents a strategic technological resource that enhances operational performance by leveraging real-time visibility and advanced simulation. Digital twins allow firms to model production and logistics processes, thereby optimizing asset utilization and minimizing waste. Studies by (Patil, 2024) and (Deepika et al., 2024) show that DTT reduces cycle time and improves demand forecasting accuracy, especially in complex manufacturing environments. Given these operational benefits, it is hypothesized that operational efficiency significantly drives the adoption of digital twin technologies, which supports Hypothesis 3 (H3).

Supply Chain Visibility

Supply chain visibility refers to the degree of transparency, traceability, and information flow across the supply chain. It includes factors such as end-to-end transparency, supplier traceability, real-time monitoring, information sharing, and event management systems. Enhanced visibility allows companies to react promptly to disruptions and make informed decisions. DTT strengthens visibility by integrating data from multiple sources and creating a digital representation of the entire supply chain ecosystem (Mubarik et al., 2024). Under RBV, this visibility is a valuable and inimitable resource that provides firms with a competitive edge. Moreover, from a Contingency Theory perspective, the effectiveness of DTT in improving visibility varies across industries based on their data-sharing culture and technology infrastructure. While prior research has highlighted the benefits of RFID and IoT in improving visibility, the role of DTT in achieving multi-tier, real-time transparency has not been adequately studied. Hence, Hypothesis 4 (H4) posits a significant relationship between supply chain visibility and DTT adoption.

Research Gaps

Despite growing interest in digital transformation within supply chains, there remain several notable gaps in the existing literature:

1. Lack of integrated studies: While many studies examine individual elements such as resilience or visibility, few have assessed the combined influence of multiple supply chain performance drivers on Digital Twin Technology adoption in a unified framework.

2. Limited qualitative insights: Most existing research is quantitative and technical, focusing on simulation models or digital architecture. There is a clear lack of qualitative studies that capture the experiential perspectives of supply chain practitioners on how DTT supports strategic outcomes.
3. Underutilization of theory: Few studies explicitly anchor their work in theories such as Dynamic Capabilities Theory, RBV, or Contingency Theory, leading to fragmented conceptual understanding. This study seeks to bridge this gap by offering a theory-driven explanation of how supply chain capabilities influence DTT adoption.
4. SME and industry diversity overlooked: Much of the literature focuses on large manufacturing firms, ignoring SMEs and non-industrial supply chains, where DTT could be equally transformative if implementation challenges are addressed.

This study contributes to the supply chain management literature by proposing a holistic, theory-grounded conceptual model that explains how four key supply chain dimensions—resilience, risk management, efficiency, and visibility—act as drivers of Digital Twin Technology adoption. This integrated view advances understanding of DTT not only as a technical tool but as a strategic capability that supports adaptive, efficient, and future-ready supply chains.

Theoretical Foundation

A strong theoretical foundation is essential to explain the relationships proposed in this study’s conceptual model, which links Digital Twin Technology (DTT) adoption to four key dimensions of supply chain performance: resilience, predictive risk management, operational efficiency, and supply chain visibility. To underpin this model, the study draws on three established theories: Dynamic Capabilities Theory (DCT), the Resource-Based View (RBV), and Contingency Theory. Together, these theories provide a multi-layered understanding of how digital twin technologies can strategically influence supply chain performance outcomes across varying organizational contexts.

Dynamic Capabilities Theory (DCT)

The Dynamic Capabilities Theory (DCT), developed by Teece, Pisano, and Shuen (1997), is grounded in the idea that organizations must continuously adapt, integrate, and reconfigure internal and external competencies to address rapidly changing environments. In the context of supply chains—where disruptions can arise from pandemics, geopolitical crises, or natural disasters—dynamic capabilities are crucial to sustaining operational continuity and long-term competitiveness. DTT plays a central role as a dynamic capability by enabling organizations to sense emerging threats, seize opportunities, and transform processes in real time. Through features such as virtual simulation, real-time monitoring, and scenario planning, digital twins help organizations proactively identify disruptions and design response strategies before these risks materialize. For example, a company using a digital twin model can simulate the impact of a port closure and instantly re-route shipments or adjust inventory allocations. This ability to predict and respond to external shocks directly enhances supply chain resilience. Moreover, DTT contributes to transformation by helping organizations reconfigure their networks, logistics plans, and supplier relationships based on real-time data, which aligns precisely with DCT’s core proposition. Therefore, DCT provides a robust theoretical framework for explaining the influence of DTT on both supply chain resilience and predictive risk management (Singh et al., 2025).

Resource-Based View (RBV)

The Resource-Based View (RBV), introduced by Barney (1991), posits that organizations gain sustainable competitive advantage by acquiring and deploying resources that are valuable, rare, inimitable, and non-substitutable (VRIN). Digital Twin Technology fits this description well—it is an advanced digital resource that leverages real-time data integration, analytics, and virtual modeling to optimize supply chain operations. When effectively implemented, DTT becomes a strategic asset that enables companies to improve decision-making, reduce costs, and adapt to market fluctuations more effectively than their competitors. From the RBV perspective, DTT enhances operational efficiency by improving demand forecasting, reducing lead times, and optimizing asset utilization. For instance, digital twins can model plant operations to minimize downtime or simulate distribution routes to reduce transportation costs. These outcomes not only improve internal efficiencies but also build capabilities that are difficult for competitors to replicate. Additionally, DTT improves supply chain visibility, which is critical for traceability, compliance, and customer satisfaction. By serving as a real-time digital mirror of physical operations, DTT ensures that organizations can observe, interpret, and act upon events across their supply chains, making visibility a strategic capability enabled by this technology. Thus, RBV substantiates the inclusion of operational efficiency and supply chain visibility as key dependent variables influenced by digital twin adoption (Ponnusamy et al., 2024).

Contingency Theory

While DCT and RBV offer powerful explanations of how and why DTT enhances supply chain performance, Contingency Theory adds an important contextual layer. This theory, rooted in organizational studies, asserts that there is no universal solution that fits all organizations; instead, the effectiveness of a technology or strategy depends on its alignment—or "fit"—with the internal and external environment of the firm (Lawrence & Lorsch, 1967). When applied to digital twin implementation, Contingency Theory highlights that the benefits of DTT will vary depending on factors such as industry characteristics, digital maturity, leadership support, and supply chain complexity. For example, a large multinational with an advanced IT infrastructure and centralized supply chain governance may find it easier to integrate digital twin systems and derive immediate value. In contrast, a small or mid-sized enterprise may struggle with the technological and financial barriers of adoption, resulting in slower or more limited returns. Contingency Theory also helps to explain why DTT's influence on resilience and predictive risk management is not uniform across organizations—it depends heavily on how well the technology is aligned with the organization's capabilities, culture, and strategic goals. Thus, this theory provides a useful lens for interpreting variations in adoption outcomes and underscores the importance of organizational readiness, cross-functional alignment, and external support (El Arif et al., 2025).

Hypotheses

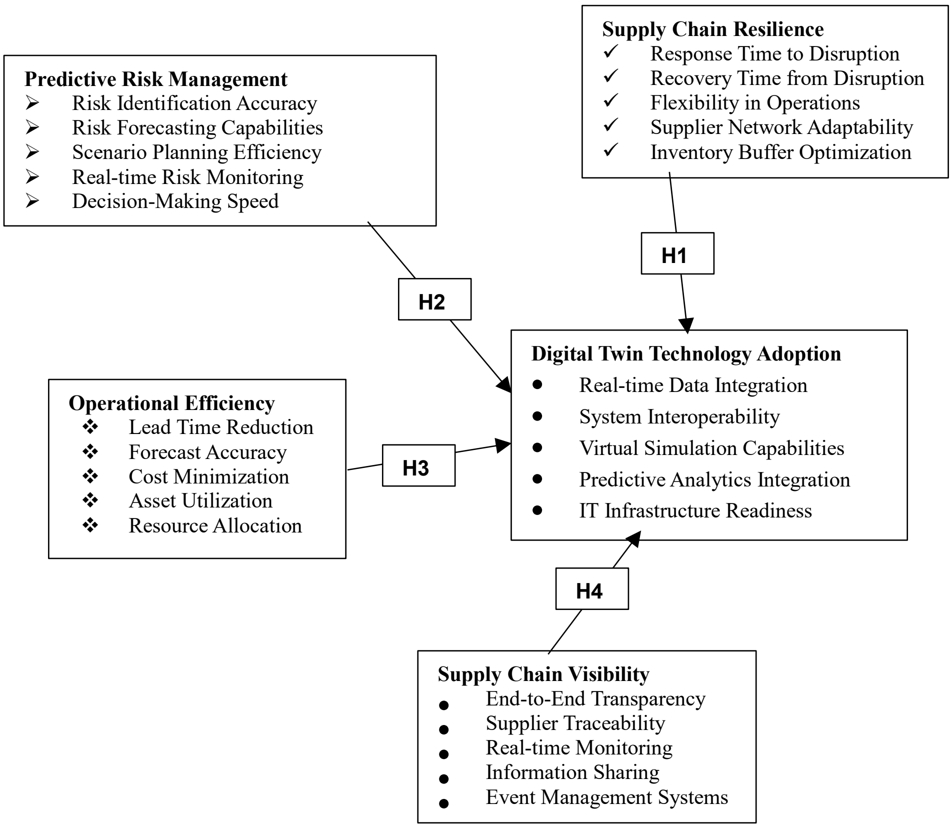
H1: There is a significant relationship between Supply Chain Resilience on Digital Twin Technology Adoption

H2: There is a significant relationship between Predictive Risk Management on Digital Twin Technology Adoption

H3: Operational Efficiency has a significant influence on Digital Twin Technology Adoption

H4: Supply Chain Visibility has a significant influence on Digital Twin Technology Adoption

Conceptual Model based on Dynamic Capabilities Theory (DCT), DCT and Contingency Theory, and Resource-Based View (RBV).



Research Methodology

This study adopts a qualitative research methodology to explore how Digital Twin Technology (DTT) enhances various dimensions of supply chain performance, specifically resilience, predictive risk management, operational efficiency, and supply chain visibility. Given the exploratory nature of the study and the need to capture deep insights from practitioners actively engaged in digital supply chain transformation, a thematic analysis approach was selected. This method allows for the identification, interpretation, and analysis of recurring patterns within qualitative data and is well-suited to understanding complex, real-world phenomena from an experiential perspective.

Research Design

The study employed a semi-structured interview design, enabling both consistency in questioning and flexibility to explore emerging themes. The research was guided by the conceptual model developed from Dynamic Capabilities Theory (DCT), Resource-Based View (RBV), and Contingency Theory, focusing on how the adoption of DTT is influenced by four dependent variables: supply chain resilience, predictive risk management, operational efficiency, and supply chain visibility (De Paoli, 2024).

Participants and Sampling

A purposive sampling strategy was used to recruit 15 interviewees who had direct involvement in supply chain operations, digital transformation, or risk management within their organizations. The participants were selected across various industries including manufacturing, logistics, automotive, healthcare, and retail to ensure a diverse range of perspectives. All interviewees held mid-to-senior roles such as Supply Chain Managers, Chief Digital Officers, IT Strategy Leads, Plant Operations Heads, and Risk Management Experts. The geographic distribution spanned both developed and emerging markets, reflecting global trends in digital supply chain innovation.

Participant Summary:

Role	Industry	Region	Experience
Supply Chain Manager	Automotive	UAE	12 years
Digital Transformation Lead	Manufacturing	Germany	9 years
Risk Analyst	Logistics	India	8 years
Operations Head	Healthcare	USA	15 years
CIO	Retail	UK	10 years
Supply Planning Director	Consumer Goods	Canada	11 years
IT Project Manager	Logistics	Singapore	7 years
Inventory Control Head	Manufacturing	UAE	14 years
Chief Innovation Officer	Technology	Australia	13 years
Procurement Manager	Retail	India	10 years
Strategy Consultant	Aerospace	Netherlands	16 years
Data Analytics Lead	Pharma	USA	9 years
Plant Operations Manager	Automotive	Japan	11 years
Logistics Network Manager	FMCG	UAE	8 years
VP – Digital Strategy	Energy	UK	18 years

3.3 Data Collection

Each interview, lasting between 45 to 60 minutes, was conducted via secure video conferencing platforms to accommodate participants from diverse geographical locations and professional backgrounds. Prior to each session, informed consent was obtained from all participants, and interviews were audio-recorded to ensure accuracy and allow for in-depth post-session analysis. All recordings were subsequently transcribed verbatim to facilitate systematic thematic coding and pattern recognition. The interview protocol was semi-structured, allowing for consistency in addressing the core themes while retaining flexibility to explore emerging insights specific to each participant’s expertise. The questions were carefully designed and aligned with the study’s four primary research objectives: first, to explore how Digital Twin Technology (DTT) enhances supply chain resilience through proactive disruption management and recovery strategies; second, to examine the role of DTT in predictive risk management, particularly its contribution to early risk identification, forecasting, and scenario planning; third, to understand how DTT supports operational efficiency by improving forecasting accuracy, resource allocation, and process optimization; and finally, to investigate how DTT contributes to enhanced supply chain visibility by enabling real-time monitoring, information flow, and end-to-end traceability across multi-tier networks. The structured approach ensured that rich, relevant, and context-specific qualitative data were collected across all four thematic domains, directly addressing the study’s conceptual framework. Probing questions encouraged participants to share specific use cases, barriers, perceived benefits, and strategic considerations (Ahmad et al., 2024).

3.4 Data Analysis – Thematic Analysis

The study employed Braun and Clarke’s (2006) six-phase framework for thematic analysis, ensuring a systematic and rigorous interpretation of the data:

- Familiarization: All transcripts were read multiple times to understand the depth and context of each interview.
- Initial Coding: Codes were generated manually and then refined using NVivo software. These included both theory-driven (deductive) and emergent (inductive) codes.
- Theme Identification: Related codes were grouped into initial themes corresponding to the study objectives.
- Theme Review: Themes were checked against the entire dataset for consistency, coherence, and recurrence.
- Theme Definition and Naming: Themes were finalized and clearly defined based on their relevance to the research questions.

- Report Writing: The most compelling narratives and quotes were selected to support key insights.

The thematic analysis yielded the following five core themes, closely aligned with the study's conceptual model and research objectives:

Emergent Themes Aligned with Research Objectives

Research Objective	Emergent Theme
Objective 1: To explore how DTT improves resilience	**Proactive Disruption Response and Recovery** – Participants highlighted how DTT enabled early warnings, faster scenario testing, and flexible recovery strategies during disruptions.
Objective 2: To examine the role of DTT in predictive risk management	**Risk Simulation and Forecasting Capabilities** – DTT facilitated predictive modeling, risk prioritization, and faster decision-making through real-time alerts.
Objective 3: To assess how DTT supports operational efficiency	**Process Optimization and Lead Time Reduction** – Respondents described how DTT led to inventory accuracy, asset utilization, and streamlined workflows.
Objective 4: To investigate how DTT improves supply chain visibility	**End-to-End Transparency and Real-Time Monitoring** – Digital twins improved traceability and information-sharing across suppliers, distributors, and logistics networks.
Cross-cutting theme	**Integration Barriers and Organizational Readiness** – Challenges such as legacy systems, workforce skills, and cost concerns were common across sectors.

Trustworthiness and Ethical Considerations

To ensure credibility and trustworthiness, the study employed member checking, where key findings were shared with a subset of participants for validation. Triangulation across roles and industries enhanced the depth of insights. Ethical approval was secured, and all participants provided informed consent, with full confidentiality and data protection maintained throughout the study. This methodology offers a robust qualitative framework to explore the complex and evolving relationship between digital twin adoption and critical supply chain outcomes. Through thematic analysis of expert insights, the study provides grounded, practice-based evidence that enriches current theoretical models and guides future implementation strategies ().

FINDINGS AND DISCUSSION

This section presents the key findings from the thematic analysis of 15 expert interviews, followed by a critical discussion linking the emergent themes to the study's conceptual model and relevant theories. The findings are organized by the four research objectives, supported by representative quotes from participants, and interpreted in the context of Dynamic Capabilities Theory (DCT), Resource-Based View (RBV), and Contingency Theory.

4.1 Theme 1: Proactive Disruption Response and Recovery

(Linked to Objective 1: Supply Chain Resilience → H1)

Participants across manufacturing, automotive, and healthcare sectors emphasized that Digital Twin Technology significantly enhanced their capacity to respond to and recover from disruptions. Many cited real-time simulations as a game-changer in managing unpredictable events such as supplier failures, transportation delays, or sudden shifts in demand. One supply chain manager from the automotive sector stated:

"When the Suez Canal incident happened, we didn't just wait for updates. Our digital twin ran four simulations in 12 hours, helping us reroute and reset inventory flows in days, not weeks."

"Digital twins gave us a head start during the pandemic. We could simulate workforce shortages, plant closures, and shipping delays before they happened. That agility made a huge difference."—Head of Global Operations, Consumer Goods Sector

"We don't just react anymore. We predict. The moment there's a disruption at one node, we already know how it will ripple across the supply chain and what levers to pull."—Supply Chain Director, Automotive Industry

This finding confirms the proposition in Hypothesis H1—that supply chain resilience significantly influences DTT adoption. Through the lens of Dynamic Capabilities Theory, digital twins help firms sense disruptions, seize adaptive options, and transform processes to maintain continuity. These proactive responses reduce response and recovery times and improve supplier adaptability, supporting the resilience dimension of the conceptual model.

4.2 Theme 2: Risk Simulation and Forecasting Capabilities

(Linked to Objective 2: Predictive Risk Management → H2)

Respondents from logistics, retail, and pharma industries highlighted that DTT enabled predictive modelling and scenario planning that traditional ERP systems could not offer. Participants valued features like risk forecasting, real-time alerts, and decision-support dashboards that allowed them to move from reactive to preventive risk management. As one risk officer from a global logistics firm noted:

"Our digital twin flagged a supplier risk two weeks before any human analysis could. We simulated scenarios and pre-emptively diversified sourcing."

"With DTT, we've moved from monthly risk reviews to real-time dashboards. The system alerts us before the supplier default becomes a crisis."—Risk & Compliance Manager, Pharmaceutical Sector

"We ran simulations for natural disasters in Southeast Asia and rerouted our shipments days before the typhoon hit. That's predictive capability we didn't have before."—Regional Supply Chain Lead, Electronics Industry

This supports Hypothesis H2 and aligns with DCT's sensing capability. The capacity to forecast potential risks and model responses in advance contributes to decision-making speed and scenario efficiency, core sub-variables in the predictive risk management construct. It also reinforces Contingency Theory, as firms with higher technological readiness and data maturity were more successful in leveraging these features.

4.3 Theme 3: Process Optimization and Lead Time Reduction

(Linked to Objective 3: Operational Efficiency → H3)

Participants widely acknowledged that DTT led to cost reductions, better asset utilization, and improved resource allocation. Particularly in fast-moving consumer goods (FMCG) and retail sectors, DTT was credited with enabling real-time production scheduling and demand forecasting, resulting in reduced lead times and waste. A plant manager from the manufacturing sector shared:

"We use a digital twin of our production line to forecast downtime and maintenance. It has helped cut lead times by 20% and improved throughput."

"We've modeled the entire warehouse digitally. It lets us optimize picking routes, reduce energy use, and increase output—all without trial-and-error on the ground."—Warehouse Automation Manager, Retail Chain

"Our digital twin flagged an equipment degradation trend a month before failure. We scheduled predictive maintenance and saved thousands in lost production."—Plant Engineering Lead, Manufacturing Firm

These findings support Hypothesis H3 and are well-grounded in the Resource-Based View (RBV). DTT emerges as a strategic, inimitable resource that optimizes internal processes and drives superior performance. Operational efficiency outcomes—such as cost minimization and lead time reduction—are tangible benefits that strongly influence DTT adoption.

4.4 Theme 4: End-to-End Transparency and Real-Time Monitoring

(Linked to Objective 4: Supply Chain Visibility → H4)

Visibility was a recurring theme across all interviews. Participants noted that DTT bridged data silos and offered a unified, real-time view of operations across suppliers, warehouses, and distribution channels. A digital transformation leader in the retail sector commented:

"We can now trace every SKU from supplier to shelf. The digital twin gives us a dashboard of live alerts—inventory mismatches, delivery delays—it's all there."

"We know where each pallet is, its condition, and when it's due—thanks to our digital twin. That level of traceability was unheard of five years ago." —Logistics Director, FMCG Company

"Our supplier onboarding now requires digital twin compatibility. If you're not visible to us, you're a liability."—Chief Procurement Officer, Healthcare Supplies

This validates Hypothesis H4 and confirms that supply chain visibility is both an enabler and a driver of DTT adoption. According to RBV, this visibility creates a valuable and hard-to-replicate advantage. Furthermore, Contingency Theory is supported as visibility gains were more pronounced in organizations with interoperable systems and strong data-sharing culture.

Cross-Cutting Theme: Integration Barriers and Organizational Readiness

While the benefits of DTT were widely acknowledged, a cross-cutting concern among participants was the difficulty of integration, especially in firms with legacy systems, low digital maturity, or budget constraints. Several participants also highlighted skills gaps and organizational resistance as obstacles. For example:

"The technology is brilliant, but unless your team can model it, interpret it, and act on it—it remains underutilized."—VP, Digital Strategy, Energy Sector

"We had to restructure our entire data architecture before the twin could deliver value. Without leadership buy-in and a clean data pipeline, it's just a digital ornament."—Chief Technology Officer, Industrial Manufacturer

"The tech isn't the issue—it's the people. Change management is harder than installing the software."—Head of Supply Chain Transformation, Oil & Gas Sector

This theme supports the Contingency Theory, illustrating that the success of DTT adoption is highly context dependent. Digital infrastructure, leadership support, and workforce capabilities all play pivotal roles in enabling or limiting the impact of digital twins.

Summary of Findings

Theme	Linked Variable	Support for Hypothesis
Proactive Disruption Response	Supply Chain Resilience	H1 Supported
Risk Forecasting and Simulation	Predictive Risk Management	H2 Supported
Process Optimization	Operational Efficiency	H3 Supported

Theme	Linked Variable	Support for Hypothesis
Real-Time Monitoring and Traceability	Supply Chain Visibility	H4 Supported
Integration Barriers	Organizational Context	Cross-cutting (Contingency Theory)

This study offers a nuanced understanding of how DTT adoption is influenced by distinct but interconnected supply chain capabilities. The findings provide empirical support for the Dynamic Capabilities Theory, demonstrating that digital twins enhance sensing, adaptation, and transformation during disruption. They also affirm the Resource-Based View by establishing DTT as a strategic asset that drives efficiency and visibility. Moreover, the Contingency Theory underscores the importance of context—technological infrastructure, digital maturity, and leadership alignment are essential for unlocking the full value of DTT. The results offer both theoretical and practical implications. For scholars, the findings validate a multi-theoretical approach to studying digital supply chain transformation. For practitioners and policymakers, the research highlights the need for ecosystem-wide collaboration, digital upskilling, and scalable solutions that promote DTT adoption across different organizational sizes and sectors.

IMPLICATIONS OF THE STUDY

This study provides practical guidance for supply chain professionals seeking to strengthen their operations through technology. It outlines how organizations can use DTT to build resilience, improve risk forecasting, and optimize operations. The findings highlight the importance of starting with smaller digital twin pilots focused on high-impact areas, and scaling gradually to broader networks once value has been demonstrated. From a managerial standpoint, the research underscores the importance of leadership support, cross-functional collaboration, and workforce training to ensure successful implementation of DTT. Managers should treat digital twins as not just IT tools but strategic assets that require integrated planning with finance, procurement, logistics, and IT departments. Change management is essential, especially in traditional industries where resistance to digital transformation remains a barrier. Socially, the adoption of DTT can create more secure and sustainable jobs by shifting roles from manual execution to data-driven decision-making and systems thinking. It also promotes safer work environments by predicting equipment failures and managing compliance risks more effectively. Economically, digital twins help reduce operational costs, prevent losses due to unanticipated disruptions, and increase ROI through optimized production and logistics. These improvements contribute to more stable supply chains, which is crucial for national and global economic resilience, particularly in post-pandemic recovery scenarios. From an environmental perspective, DTT facilitates waste reduction, energy efficiency, and resource optimization by simulating sustainable scenarios and minimizing overproduction or excess inventory. Organizations using digital twins are better positioned to meet sustainability targets, reduce carbon emissions, and transition toward greener supply chain practices.

CONTRIBUTION AND ORIGINALITY VALUE

This research makes a novel contribution by being one of the first qualitative, theory-driven studies to holistically explore how multiple dimensions of supply chain performance influence the adoption of Digital Twin Technology. By grounding the study in Dynamic Capabilities Theory, Resource-Based View, and Contingency Theory, it offers an integrated theoretical lens to understand not only what digital twins can achieve but also why and under what conditions they succeed. The use of rich, cross-sectoral interview data from practitioners across global regions adds originality and practical depth, filling a gap in both academic literature and industrial practice.

RECOMMENDATIONS FOR FUTURE RESEARCH

Given the emerging nature of Digital Twin Technology in supply chains, several avenues for future research are recommended:

- **Quantitative Validation:** Future studies should employ structural equation modeling (SEM) or partial least squares (PLS-SEM) to quantitatively test the conceptual model on a larger sample across different regions and industries.
- **Longitudinal Case Studies:** In-depth, longitudinal case studies could explore the maturity path of digital twin adoption and how performance metrics evolve over time.
- **Focus on SMEs:** Research should investigate how small and medium-sized enterprises (SMEs) can adopt DTT despite resource constraints, including the role of government subsidies and digital ecosystems.
- **AI and DTT Integration:** Future studies can explore how DTT integrates with AI, machine learning, and blockchain for real-time autonomous supply chain decision-making.
- **Ethical and Governance Dimensions:** More research is needed on data privacy, algorithmic bias, and ethical concerns related to the use of DTT in multi-stakeholder supply chains.

CONCLUSION

This study explored the role of Digital Twin Technology in enhancing supply chain resilience and predictive risk management, framed by a conceptual model grounded in

DCT, RBV, and Contingency Theory. Through rich qualitative insights drawn from 15 expert interviews, the study confirmed that DTT adoption is significantly influenced by four key performance enablers: resilience, risk management, operational efficiency, and visibility. The findings demonstrate that digital twins empower organizations to anticipate disruptions, simulate recovery, improve forecasting, reduce operational inefficiencies, and provide unprecedented real-time visibility across the supply chain.

While the benefits are compelling, the study also emphasizes that the success of digital twin implementation is contingent on organizational readiness, leadership alignment, cross-functional capabilities, and technological infrastructure. As the world moves toward increasingly complex and uncertain supply chain environments, digital twins are no longer optional innovations—they are becoming strategic imperatives. In conclusion, this research contributes to a growing body of knowledge on digital supply chain transformation and provides a practical roadmap for organizations seeking to enhance competitiveness, sustainability, and resilience in a volatile global economy. As supply chains continue to evolve in the face of technological, environmental, and geopolitical challenges, Digital Twin Technology will be pivotal in shaping the future of intelligent, adaptive, and sustainable supply networks.

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