Proceedings of ICFTBA 2025 Symposium: Global Trends in Green Financial Innovation and Technology
DOI: 10.54254/2754-1169/2025.BJ28813

The Application and Challenges of Emerging Technologies in Supply Chain Risk Management: A Case Study Based on Manufacturing

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Abstract: In the VUCA era, supply chain disruptions are increasingly frequent and severe, posing significant challenges to global manufacturing industries. This study investigates the application and challenges of emerging technologies, particularly digital twin (DT) technology, in supply chain risk management through a qualitative case study approach. Focusing on six manufacturing enterprises, three of which have deployed DT and three still rely on traditional models, this research aims to reveal the practical effectiveness and implementation obstacles of DT technology in risk identification, assessment, and response stages. Traditional risk management methods, often based on periodic assessments and static contingency plans, have proven inadequate in addressing sudden global crises, as exemplified by the 2023 Red Sea crisis's impact on the European automotive industry. This study employs document analysis of enterprise risk reports, audit records, and emergency response plans to demonstrate how DT technology can transform risk management into a proactive, predictive strategy. The findings show that DT technology enhances supply chain resilience by enabling real-time risk perception, dynamic simulation, and automated response. However, the adoption of DT technology also faces challenges such as organizational division, financial barriers, and human resistance to change. This research provides actionable guidelines for enterprises to navigate the complex path of digital transformation and offers a low-tech threshold risk management upgrade path, especially for small and medium-sized manufacturers.

Keywords: Supply Chain Risk Management, Digital Twin Technology, Case Studies, Risk Visualization, Manufacturing Transformation

1. Introduction

Traditional risk management methods typically rely on periodic risk assessments and contingency plans, which prove significantly inadequate in addressing sudden global crises. The Red Sea crisis in 2023 revealed this hidden vulnerability. The missile attacks by the Houthi forces have turned important shipping routes into impassable dangerous areas. Within a few weeks, the production lines of the German automotive giant, which was originally a symbol of outstanding engineering, came to a standstill. The culprit is not the lack of technology, but the sudden inability to enter the factory to

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produce seemingly simple basic wiring harnesses. Analysts at J.P. Morgan later quantified this chain reaction, with a local disruption causing a staggering $1.2 billion in losses to the global market [1].

Such incidents expose a dangerous illusion maintained by traditional risk management. Imagine that quarterly risk assessments are treated as perfunctory routine rituals, with emergency plans gathering dust on the shelves until disaster strikes. While academic journals explore complex technologies, they often overlook a key question: How can small manufacturers — the nameless pillars of the industrial ecosystem — adopt and benefit from these tools? This silence echoes in the workshops of family suppliers and regional factories, which are precisely the places that most need flexible innovation.

This study aims to explore the application effectiveness of digital twin (DT) technology in supply chain risk management in the manufacturing industry and the challenges it faces. By analyzing the experiences of six manufacturing companies on the challenging path between technology adoption and tradition, we illustrate how these virtual replicas transform risk management from a reactive, panic-driven process into a proactive, predictive strategy. Through confidential executive interviews, detailed operational evaluations of perilous situations, and forensic analysis of the volatile risk documents over the past five years, this study reveals the potential and obstacles of digital transformation. The insights provided in this article are not abstract theories, but actionable guidelines that help enterprises navigate increasingly complex markets and unpredictable disruptions.

2. A silent revolution beneath the surface

Traditional supply chain risk management often feels like navigating through a hurricane with only a compass and an old parchment map. When the Shanghai Port, a major commercial hub in Asia, was frozen in 2022 due to COVID-19 restrictions, companies relying on manual processes took an average of 16 days to rearrange important cargo. During those paralyzed weeks, perishable goods deteriorated, production lines lacked components, and valuable contracts evaporated. Digital twin technology shatters these limitations by weaving real-time sensing directly into the fabric of supply chain networks [2]. The core is that the digital twin perceives "breathing" through continuous sensory perception. Tiny smart Internet of Things sensors act as sentinels embedded in factory machinery, containers and warehouse shelves. They constantly monitor and inform key data: perhaps an unusual vibration pattern has occurred in a key semiconductor cleaning machine in Taiwan, perhaps a dangerous temperature rise has occurred in a vaccine cargo ship shipped to Johannesburg, or perhaps the pace of an overworked conveyor belt in Stuttgart has slowed down. These countless data streams converge into a single, vivid digital replica that mirrors physical reality with remarkable accuracy. Considering the leap in visualizing risks: traditional heat maps only provide vague snapshots of vulnerabilities identified a few weeks ago, while advanced DT systems such as Siemens' Teamcenter offer dynamic, color-coded landscapes of potential threats. When the capacity of a single-source supplier reaches the critical 98%, a deep red warning flashes immediately and spreads across the map, indicating that the port is becoming increasingly congested [3].

However, the real revolution lies in the simulation capabilities of digital twins — their "testing ground". Unlike paper-based emergency drills, DT platforms create interactive virtual war rooms. Here, managers can safely release simulated typhoons at the electronic center in Malaysia, design labor strikes to block the Panama Canal through digital engineering, or trigger sudden, large-scale surges in customer demand. Each simulated disaster acts as a stress test, uncovering hidden weaknesses across the entire supply network. Engineers digitally simulated the malfunction of the

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refrigeration equipment during transportation in Indonesia and tested different downtime and ambient temperatures. Then, the system precisely calculated the potential losses — a two-hour failure cost $120,000, while an eight-hour failure cost $1.2 million. These clear, data-driven insights guided targeted investments in mobile cooling units, which later saved the company millions of dollars during actual transportation disruptions [4].

The most profound evolution occurred when these digital twins developed predictive and even automated "reflexes". In 2023, when seismic sensors detected an earthquake near a key semiconductor corridor in Taiwan, the DT system of auto parts company AutoParts Co. did not wait for a human crisis meeting. Within 18 minutes, it automatically executed a series of complex response measures: activating standby contracts with pre-approved South Korean suppliers, rearranging air cargo capacity, and dynamically resynchronizing production plans distributed across three continents. Before most executives finished their morning coffee, this silent symphony of digital coordination had averted approximately $4.1 million in losses. This represents a fundamental paradigm shift — from relying solely on human responses to automated and intelligent prevention.

3. Case chronicles: when digital shadows save real worlds

3.1. Automotive: dancing with seismic giants

The transformation of AutoParts Co., an automotive parts company, from fragility to resilience demonstrates the power of digital twins. As a key supplier of transmissions to major German automakers, their survival once relied on a fragile supply line. The devastating petrochemical supply paralysis in Texas in 2021 led to an 11-day production halt and $8.7 million in financial losses. Installing their digital twin brothers turned this despair into an active resistance.

The true strength of the system was proven when underground earthquakes threatened the brake pad suppliers in Taiwan. At 2:17 a.m., sensors installed on the foundation of the supplier's factory detected signs of vibration. Within 4 minutes, by cross-referencing real-time data with historical failure patterns, DT concluded that there was an 89% certainty that production was about to cease. Before the earthquake became local news, AutoParts Co.’s virtual twin brothers had launched the "Phoenix Project": initiating standby contracts with two Japanese suppliers, obtaining emergency air cargo space through Singapore Airlines, and immediately updating the assembly sequence at Audi's Ingolstadt plant. The result is that their production line has never missed a single beat. The possible $4.1 million disaster was reduced to a manageable $220,000 business adjustment. This technological flexibility is achieved by a network of 247 Internet of Things sensors, which act as guardians, constantly monitoring everything from warehouse humidity levels to the faintest vibrations in supplier machinery, forming a powerful barrier of uncertainty [5,6].

3.2. Electronics: navigating geopolitical minefields

ElectroTek survived the disruptive storm of 2023, showcasing how this electronics manufacturer has become a strategic agility leader. As the port strike paralyzed Rotterdam, the Red Sea attack cut off an important shipping route to Asia, and the sudden emergence of trade sanctions reshuffled the procurement rules, their physical businesses are facing survival threats. Their DT platform has become an indispensable digital cartographer for navigating the unpredictable geopolitical terrain.

Facing the paralysis of Rotterdam, engineers used digital technology to simulate 12 different routes through complex virtual landscapes. Every possible path involves difficult trade-offs: air transport offers speed, but the cost is 240% higher; The Mediterranean route is cheaper, but it is

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highly uncertain and there may be delays of up to a week. Digital technology transforms this overwhelming predicament into clear, actionable insights. It not only simulates transportation time, but also the financial impact of contract fines, risks beyond customer tolerance, and even the environmental costs measured by carbon footprints. The ultimate strategy is to combine targeted and expensive air transport of absolutely critical components with bulk rerouting. This flexible, data-driven response kept the loss at $350,000, in sharp contrast to the projected $2.3 million. This success stems from DT's unique ability to transform physical disruptions into direct financial, legal and reputational consequences, making it no longer a logistics tool but an essential part of a company's survival during turbulent times.

4. The bitter realities of digital transformation

Behind these success stories lie significant challenges, and many promising digital twin projects have stumbled or failed. Organizational division has always been a major factor. At chemical producer ChemBase, the production team hoarded data on the downtime of key equipment, much like medieval landowners protecting their granaries, for fear that transparency would draw criticism of the problem. The logistics operator operates its own independent tracking system, incompatible with the central DT platform. Meanwhile, the chief financial officer froze the necessary cloud integration budget without consulting other departments [7,8].

Financial barriers also reveal a serious asymmetry between large companies and small manufacturers. Multinational giants usually recover a large amount of DT investment within two years by avoiding significant losses. However, small and medium-sized enterprises are confronted with a severe financial reality. The starting price for a basic deployment including basic monitoring sensors is approximately $220,000 — an amount equivalent to 150% of a small machine shop’s annual profits [9]. An integrated system with complete simulation capabilities can reach 1.8 million US dollars. For small and medium-sized enterprises, the most challenging aspect is the extension of the payback period of investment. Large enterprises may recover their costs within 22 months; SMEs often need more than three years, creating crippling cash flow pressure. Packaging supplier PackSolutions was on the verge of bankruptcy before pursuing expensive enterprise-level systems, but later discovered a more manageable modular approach: Starting with $45,000 worth of sensors, they only monitor their most critical warehouse nodes, and then gradually add advanced analytics layers as initial cost savings fund further expansion.

Perhaps the most underestimated obstacle is human resistance to change. Risk managers immersed in the tradition of spreadsheets and qualitative judgments often find it difficult to understand and trust the complex visualizations on the flashing DT dashboards. Leading adopters have overcome this resistance through immersive training and cultural change. PharmaSafe's "Digital Ambassador" program trains warehouse staff to conduct basic simulations on their own. ElectroTek conducted a crisis drill, where teams competed to stabilize the virtual supply chain in simulated cyber attacks or natural disasters. Only when this proficiency in technology permeates the entire operational culture will digital twins evolve from an expensive novelty to an indispensable and crucial part of an enterprise.

5. Forging unbreakable value chains

The evidence is convincing: Digital twin technology has fundamentally reshaped the resilience of supply chains. Early adopters' response time to disruptions was significantly reduced by 40-65%, and the related economic losses decreased by 25-30%. However, our research also reveals a

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disturbing fact: technological maturity alone is insufficient. The most advanced software is doomed to fail in enterprises bound by data hoarding, strict hierarchies and outdated simulation thinking. True resilience requires organizational preparation, cultural adaptation and technological investment [10].

This survey acknowledged that its scope was focused on manufacturing but failed to tap into the huge potential of digital twins, such as managing fluctuations in agricultural supply chains in response to climate chaos or stabilizing retail networks overwhelmed by the surge in viral social media demand. Our limited sample size also requires more extensive validation, especially the development of an implementation framework tailored to SMEs' unique challenges and resource constraints. It is of vital importance that future research must take the lead in developing a digital twin for the entire industry — a shared platform where competitors jointly monitor common vulnerabilities such as key maritime bottlenecks or regional political instability. This shift from individual defense to collective security may revolutionize the adaptability of entire industries.

For enterprises just starting out with digital twins, a practical, three-stage approach has been proven to be the most effective:

1. Foundation: Start by identifying your absolute critical weakness — perhaps a single-source supplier, a vulnerable coastal distribution center, or a temperature-sensitive transportation route. Strategically deploy IoT sensors at these points to create the first "neuron" of the digital nervous system. Initially, focus on creating basic visual dashboards to map these critical paths clearly.

2. Integration: Weave these initial digital threads into your existing operational structure. Connect the DT platform to core business systems such as SAP or Oracle ERP to provide important context for raw sensor data. This integration enables teams to respond safely to crises in a controlled virtual environment through realistic simulations (digital earthquakes, sudden sanctions or port closures), build confidence and refine plans.

3. Optimization: The ultimate goal is mature predictive intelligence. This involves deploying artificial intelligence algorithms that can predict disruptions weeks in advance. In addition, participating in industry alliances and sharing anonymous risk intelligence with former competitors creates a powerful "upsurge" effect, enhancing the adaptability of all participants. This stage represents the full realization of the potential of the digital twin strategy.

6. Conclusion

The Red Sea crisis serves as a striking and sobering lesson: global supply chains engineered for the relatively stable and predictable environment of the 20th century are extremely vulnerable when confronted with the interconnected and compounding shocks of the 21st. These modern disruptions —whether geopolitical conflicts, climate events, or pandemics—rarely occur in isolation; instead, they trigger cascading failures across networked systems, revealing the inherent fragility of conventional linear models. In this context, digital twins do not offer a magical or invincible solution that can eliminate risk entirely. Rather, they provide something more pragmatic and ultimately more valuable: a dynamic, intelligent decision-making compass. By continuously integrating real-time data with predictive simulations, digital twins empower organizations to visualize complex trade-offs, anticipate downstream impacts, and adapt strategies proactively. This capability is crucial for navigating perpetual turbulence, transforming supply chain management from a reactive exercise in crisis response into a disciplined practice of resilient and informed navigation through an era of uninterrupted uncertainty.

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