Digital Twins Drive Supply Chain Resilience: A Case Study of Suzhou Boyang Chemical Plant and Baikuang Debao Base

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Abstract. Under the new normal of global "high uncertainty, high complexity, and high externalities", traditional supply chains expose significant vulnerabilities in extreme shocks. This study, with the theme of "digital twin-driven supply chain resilience enhancement", selects Suzhou Boyang Chemical Plant (discrete-multi-variety-high control) and Baikuang Debao Base (continuous-heavy asset-green transformation) as dual cases. Based on operational data from 2021 to 2023, a before-and-after A/B experimental design is adopted to quantitatively evaluate the four-dimensional indicators of resistance, recovery, adaptability, and evolution. The results show that digital twins have reduced the leakage probability of Boyang by 38%, compressed the recovery time by 87%, reduced unplanned tank stoppages of Baikuang by 55%, decreased annual carbon emissions per ton of aluminum by 10%, and precipitated 127 pieces of reusable resilience knowledge. The study refines a common resilience enhancement loop of "second-level perception-minute-level simulation-hour-level decision-making", providing empirical evidence and policy insights for governments and enterprises to develop a cross-industry resilience governance paradigm.

Keywords: Supply chain resilience, digital twin, data.

1. Introduction

Currently, the world is experiencing profound changes unseen in a century. Economic globalization faces resistance, trade protectionism has increased, the Russia-Ukraine conflict continues to intensify, and the global governance system is undergoing a profound transformation. Various uncertainties, instabilities, and unpredictable events have significantly increased. Situations such as raw material shortages, production stagnation, product supply disruptions, and logistics bottlenecks occur frequently, greatly hindering the flow of resources such as people, money, and materials. This has brought significant impacts to the supply chain, which is like "a single hair pulling can affect the whole body," and the vulnerability and interruption risks of the supply chain have become increasingly evident [1]. How to enhance resilience without sacrificing efficiency has become a core issue that the supply chain urgently needs to address.

Supply Chain Resilience refers to the comprehensive ability of a supply chain to maintain its core functions or swiftly recover to its original or improved state through its capacity to predict, absorb, adapt, and rapidly recover in the face of internal and external shocks such as natural disasters, epidemics, geopolitical conflicts, sudden changes in demand, supplier bankruptcy, etc [2]. Its core objective is to minimize the losses incurred by disruptions and even transform crises into competitive advantages.

The resilience of the supply chain is spirally composed of "four forces": first, resistance such as strategic inventory and multi-source procurement to buffer initial shocks; then, recovery such as enabling backup suppliers or rerouting transportation to quickly restart operations; next, adaptation such as shifting to localized production or digital upgrades during the pandemic to dynamically reshape structures and processes; and finally, evolution such as solidifying experience into more flexible contract terms, risk warning systems, and long-term design optimization to enable the supply chain to continuously iterate and become stronger through repeated shocks [3].

Digital Twin, with its capability of real-time perception-synchronous simulation-predictive decision-making-closed-loop optimization, provides a new technological path for supply chain resilience [4]. However, existing research has mostly focused on discrete manufacturing or retail scenarios, and there is still a lack of systematic evidence on the resilience enhancement mechanisms for two extreme scenarios: high-risk processes with multiple varieties in the chemical industry and heavy-asset continuous metallurgy.

This study takes Suzhou Boyang Chemical Plant,discrete-multi-variety-high control, and Baikuang Debao Base, continuous-heavy asset-green transformation as dual cases. By comparing operational data from 2021 to 2023, it quantitatively verifies the actual gains of digital twins in four dimensions: resistance, resilience, adaptability, and evolution. The research results aim to provide a basis for government, enterprises, and investors to make supply chain resilience decisions, moving from mechanism to practice and from micro to macro levels.

This article selects two cases for a case study, incorporating both Suzhou Boyang Chemical Plant and Baikuang Debao Base into the supply chain research. This is primarily based on their complementary advantages in the triple dimensions of complexity, typicality, and generalizability. Boyang Chemical Plant provides a micro-resilience experimental field for complex products and multi-risk coupling, while Baikuang Debao Base offers a macro-resilience testing ground for heavy assets and green constraints. The combination of the two enables a closed-loop verification of supply chain resilience research, from mechanism to practice and from micro to macro.

2. Enhancing Supply Chain Resilience Driven by Digital Twins

Digital twins can be considered as a resilience enhancement loop: real-time perception → synchronous simulation → predictive decision-making → closed-loop control → continuous evolution [5]. Boyang Chemical Plant and Baikuang Debao Base, representing the extreme scenarios of discrete-multi-variety and continuous-heavy asset, respectively, serve to validate the universality and differentiated paths of the loop across different supply chains.

2.1. Comparison of Digital Twin Architectures

Table 1. Comparison of digital twin architectures

Dimension	Boyang Chemical Plant (Discrete Chemical)	Baikuang Debao Base (Continuous Metallurgy)
Twin Granularity	Using 'reactor-batch-order' as the smallest unit, tracking at SKU level	Using the 'electrolytic cell-area-day' as the smallest unit, energy consumption-production coupling
Key Entity	Hazardous chemical tanks, clean rooms, hazardous goods vehicles	Electrolytic cell, waste heat boiler, aluminum ladle
High-frequency data	Temperature, pressure, pH, transportation in-transit vibration	Cell voltage, series current, aluminum liquid temperature, carbon consumption
Risk event library	Leakage, formulation deviation, transportation restrictions	Power outage, cell condition fluctuation, coal price surge
Twin engine	Discrete-continuous hybrid simulation based on AnyLogic	Real-time process optimization based on PI System + Aspen HYSYS

As shown in Table 1, it can be observed that Boyang's digital twin treats each batch of hazardous chemicals as the smallest granule, utilizing AnyLogic for discrete simulation, focusing on leakage, traffic congestion, and formula errors; while Baikuang's digital twin treats each electrolytic cell + each day as the smallest granule, utilizing PI + Aspen for process optimization, focusing on power outages, cell conditions, and coal prices. The former emphasizes flexibility, while the latter focuses on steady-state conditions.

2.2. Data Access and Resilience Indicator Mapping

2.2.1 Boyang

Table 2 compares the 6-month rolling averages of Boyang Chemical Plant in 2021Q1 before the launch of digital twins and 2023Q4 after the launch using an A/B comparison, revealing the quantitative transitions in "resistance, recovery, and adaptability-evolutionary capacity" before and after the introduction of digital twins.

Table 2. Comparison of Boyang Digital Twin before and after its launch

Indicator	2021Q1	2023Q4	Change
Safety Redundancy Factor	0.73	1.21 ↑	Real-time level + ETA algorithm ensures that even the slowest replenishment truck arrives before the tank is empty, redundancy from insufficient to sufficient
Alternative Supplier Activation Time	38 h	14 h ↓	Twin automatically matches the shortest inventory + lead time combination, enabling speed increased by 63%
Stockout Recovery Cycle	26 h	9 h ↓	Twin calculates additional production capacity - inventory gap in seconds, compressing recovery time by 65%
Urgent Production Flexibility	18 h	6 h ↓	Production line switching matrix + online comparison of recipe library, shortest changeover path shortened by 67%
Area Under the Risk Curve for 72 h Typhoon Scenario	1.96	0.42 ↓78%	The twin systems provide monthly recharge accident data, resulting in an overall downward shift in the risk curve
Accident-Twin Knowledge Base Entries	0	127 ↑	Each abnormal event automatically precipitates into a twin script, forming self-evolution

As can be observed from Table 2, digital twins transform "pre-existing vulnerabilities" into "pre-emptive buffers," significantly enhancing resilience. Digital twins not only address immediate issues but also solidify experience into long-term competitiveness—a typical manifestation of evolutionary power. Shocks result in high stockouts and long downtime before going live. Shocks are absorbed by pre-emptive redundancy, instantaneous decision-making during the event and instantaneous recovery afterwards, after going live, and each crisis makes the digital twin model smarter.

2.2.2 Baikuang

Table 3. Comparison of Baikuang Digital Twin before and after its launch

Indicator	21-Oct	23-Oct	Change
Aluminum Tonnage Electricity Consumption Fluctuation σ(ΔkWh/t)	1.60%	0.44 % ↓	Second-level PLC feedback and twin pole distance correction, fluctuations are compressed to within ≤0.5% target
Rectifier Unit Trip for 1 Hour ‘Expected Production Loss’	6.80%	1.7 % ↓	The twin system provides a load transfer plan 30 minutes in advance, reducing the loss from 6.8% to less than 2%
30-day Green Electricity Proportion Flexibility ΔGmax	4 p.p.	18 p.p. ↑	Real-time integration with power grid dispatch + coal price futures API, green power ratio can be increased by 18 percentage points within 30 days
Marginal Carbon Emission per Tonne of Aluminium (tCO_2/tAl)	1.95	1.68 ↓	After switching to a high proportion of green electricity, marginal carbon emissions decrease by 14%
Restart Time After Shutdown	2.5 h	0.9 h ↓	Twin load transfer + tank condition preheating script issued with one click
Accident Scenario Script for Twin Knowledge Base	0	23 ↑	Each real blackout is automatically archived as a reusable twin scenario

Table 3 compares the 12-month rolling averages of the digital twin of the Baikuang Debao Base before, October 2021, and after, October 2023, its launch, using the same framework of resistance, adaptability and recovery-evolution to quantify the changes in indicators.

From Table 3, it can be observed that after the launch of the data twin, there has been an improvement in resistance, electricity consumption has become more stable, and the loss due to disturbances has decreased. There has also been an enhancement in adaptability; the energy structure can be rapidly rearranged in response to policy and market signals. Before the launch, electricity consumption fluctuated significantly, and a single outage resulted in a loss of nearly 7%. After the launch, electricity consumption fluctuations are corrected in seconds, and the loss due to outages is less than 2%. Additionally, within 30 days, the green electricity can be freely increased or decreased by 18%. The twin system becomes smarter with use.

2.3. Path to Enhancing Resilience

2.3.1 Boyang: "4R" closed loop driven by digital twins

128 fiber optic strain gauges are affixed to the tank wall, pushing stress, temperature, and liquid level data to the cloud every second. The twin model runs a finite element analysis every 30 seconds. Once the stress approaches the 80% threshold, the system automatically generates a detour route and pushes it to the driver's mobile app, eliminating the need for on-site manual intervention and directly reducing the leakage risk by 38%. Once the Manufacturing Execution System (MES) signals batch non-conformity, the twin scheduling engine is activated within 5 seconds. Mixed Integer Linear Programming (MILP) is used to calculate the nearest available production line, the shortest path for Automated Guided Vehicle (AGV), and the amount of cleaning solvent. After scanning confirmation, the switch is completed within 45 minutes, compared to the previous 6 hours, and solvent waste is reduced by 12%. Safety thresholds and model parameters are updated in real time, and the knowledge base has accumulated 127 pieces of experience, compressing the training period for new employees from two weeks to three days.

2.3.2 Baikuang: Twin and AI energy-saving model for continuous processes with heavy assets

Over 3,000 measuring points are set up on the electrolytic cell, with temperature, current, and electrode gap data being uploaded to the cloud in seconds. The twin model runs a coupled calculation every 5 seconds, and if the electrode gap deviation exceeds 2 mm, it immediately prompts the AI to perform fine adjustments. As a result, the probability of anode effect has been reduced from 2.1% to 0.9%, and unplanned cell shutdowns have decreased by 55%. The day-ahead and real-time dual markets capture the spot price of green electricity and carbon price every 15 minutes, and the twin system performs real-time rolling optimization of the "electrolytic cell load - self-generation coal power - green electricity" combination. The carbon emissions per ton of aluminum have decreased from 1.95 to 1.68 tCO_2e per year, a reduction of 10%, and the proportion of green electricity can be flexibly increased or decreased by 18 percentage points within a day. In extreme coal price scenarios, it automatically switches to "load reduction + outsourced green electricity", resulting in a 3% increase in marginal profit. The Long Short-Term Memory (LSTM)-attention network is used to learn from offline logs of 3 years of cell age-efficiency-failure data, predicting the efficiency decay of a single cell over the next 6 months. The optimal overhaul window is locked 30 days in advance, the overhaul interval is extended by 8%, and the series efficiency decay rate is reduced from 0.35%/month to 0.28%/month.

3. Conclusion

The common conclusion shows that digital twin technology has successfully transformed resilience management from post-event remediation to pre-event immunity by achieving second-level perception, minute-level simulation - hour-level decision-making. In terms of industry differences, the discrete chemical industry needs to focus on the dynamic scheduling problem under the multi-variety - multi-risk coupling scenario, while the continuous metallurgical industry needs to address the energy and production capacity coordination issue in the context of high energy consumption - high asset specificity. Through the dual case study of Boyang and Baikuang, it further verified the effectiveness of digital twins in enhancing the resilience of different supply chains, specifically manifested in the process of real-time synchronization, predictive intervention, and closed-loop optimization. At the same time, these two cases also reveal the differentiated implementation points of digital twins in terms of granularity, decision-making frequency, and optimization objectives for discrete and continuous processes.

Based on these industry characteristics, it proposes the following policy recommendations: For chemical industrial parks, the government can establish a hazardous chemical twin-sharing cloud to promote emergency collaboration across enterprises; for high-energy-consumption industries, the government should introduce a twin and green electricity subsidy policy to encourage enterprises to utilize real-time simulation technology to optimize energy consumption structure. When the virtual river begins to reflect the real mountains, digital twins are no longer cold code, but a crystal seed embedded in the heart of the supply chain. It quietly sprouts, grows real-time sensing branches and leaves, and weaves a transparent net that breathes - the wind leaves traces in the net, rain writes warnings in the net, and crises are gently folded into chapters that can be read in the future before they even approach. Tomorrow, perhaps it just needs to softly ask the screen, Are you ready? And the entire industrial chain will nod in sync in the light and shadow, translating the waves of uncertainty into ripples of certainty.

References

[1] Ma X Y, Huang M Z, Yang M X. Research on the influencing factors of supply chain resilience: based on SEM and fsQCA. Systems Engineering-Theory & Practice, 2023, 43 (9): 2484-2501.

[2] Shishodia A, Sharma R, Rajesh R, Munim Z H. Supply chain resilience: a review, conceptual framework and future research. The International Journal of Logistics Management, 2023, 34 (4): 879-908.

[3] Cheng Q Q. Research on the connotation, mechanism, and measurement of industrial and supply chains - based on the resilience of regional industrial and supply chains and its implications for Nantong. Canjianwang, 2022-12-30.

[4] Tao F, Qi Q L, Wang L H, Nee A Y C. Digital twins and cyber-physical systems toward smart manufacturing and industry 4.0. Engineering, 2019, 5 (4): 653-661.

[5] Wang F Y, Sun T, et al. Digital twin network (DTN): concepts, architecture, and key technologies. Acta Automatica Sinica, 2021, 47 (3): 569-582.