



Research on Supply Chain Resilience of Manufacturing Enterprises Enabled by Digitalization

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Abstract: The vulnerability of global supply chains has been fully exposed in various emergencies in recent years. As a pillar industry of the national economy, the construction of supply chain resilience for manufacturing industry has been elevated to the national strategic level. At the same time, the in-depth development of digital technologies has provided a brand-new research paradigm and practical path for supply chain risk management. This paper systematically combs the theoretical evolution context of digital empowerment for supply chain resilience of manufacturing enterprises, constructs a triple mechanism framework of "information transparency - intelligent decision-making - relationship coordination", and extracts practical paths for supply chain resilience construction in the digital context by combining empirical research results and typical enterprise cases at home and abroad. The study finds that the impact of digitalization on supply chain resilience presents a non-linear characteristic, with significant threshold effect and context dependence. Enterprises should avoid blind technology-oriented investment, and instead focus on the coupled and coordinated development of digital capabilities and risk governance capabilities. The conclusions of this paper can provide theoretical reference and decision-making reference for the research on digital transformation of manufacturing industry and the safety and stability of industrial and supply chains.

Keywords: digital empowerment; supply chain resilience; manufacturing industry; risk management; industrial digitalization

1. Introduction

1.1 Realistic Background and Problem Formulation

The severity of current supply chain disruption risks far exceeds that of previous historical periods. A series of black swan and gray rhino events, including the periodic shutdown of global supply chains caused by the COVID-19 pandemic, the paralysis of Asia-Europe logistics routes caused by the Suez Canal blockage, and the shocks to energy and raw material supply caused by geopolitical conflicts, have continuously impacted the normal operation foundation of manufacturing enterprises[1]. As the world's largest manufacturing country, China has the world's largest and most complete industrial system with comprehensive supporting facilities, yet it has long faced "chokepoint" dilemmas in fields such as high-end chips, key components, high-end equipment, basic industrial software and core raw materials, with weak independent and controllable capabilities of the industrial and supply chains[2]. This structural contradiction of "being large but not strong, comprehensive but not superior" has been further amplified under the impact of supply chain crises, becoming a core bottleneck restricting the high-quality development of the manufacturing industry.

Traditional supply chain management takes lean efficiency optimization as the core goal. Models such as zero inventory management and just-in-time production have created significant economic value in a stable market environment, but exposed extremely strong vulnerability in the face of sudden accidents, which are likely to trigger chain risks such as supply cut-off, production suspension and unsalable products. When the operation logic of "efficiency first" encounters the realistic test of "risk priority", manufacturing enterprises are forced to re-examine the underlying logic of supply chain design, and supply chain resilience has gradually replaced a single efficiency goal as the core priority of supply chain management in the new era [3]. At the same time, the cluster breakthrough of digital technologies such as big data, artificial intelligence, internet of things and blockchain has provided unprecedented technical support for supply chain risk identification, early warning and rapid response. The in-depth integration of digitalization and supply chain resilience is comprehensively reshaping the competition rules and development pattern of the manufacturing industry.

1.2 Definition of Core Concepts

Digital empowerment is the process of in-depth integration and reconstruction of digital technologies with organizational operation processes and business models. Based on the dynamic capability theory, this paper defines digital empowerment as the process in which enterprises rely on digital infrastructure to reconstruct resource arrangement methods and value

creation logic, form dynamic capabilities to perceive changes in the external environment, capture market opportunities and reconstruct internal and external resources, and finally achieve the dual improvement of decision-making quality and operation efficiency.

The concept of supply chain resilience originates from the field of ecology and has formed a rich connotation system through interdisciplinary evolution. Christopher & Peck (2004) defined supply chain resilience as the ability of a system to restore its original state or achieve a better operation state after being disturbed. Combined with existing research results and the practical characteristics of the manufacturing industry, this paper adopts an integrated definition, that is, supply chain resilience is the systematic ability of a supply chain network to maintain core operation functions and achieve continuous improvement through redundant design, flexible adjustment and collaborative evolution under external shocks[4-5].

1.3 Research Significance and Framework

From a theoretical perspective, the interdisciplinary research on digitalization and supply chain resilience is still in its infancy. Most existing literature focuses on the application of a single technical tool or analysis of specific industry scenarios, lacking systematic mechanism explanation and integrated analysis framework [4]. This paper attempts to bridge the two research fields of digital transformation and supply chain management, and further expand the research boundary of enterprise risk management theory.

From a practical perspective, the investment in digital transformation of manufacturing enterprises continues to expand, but the transformation effects are uneven. Some enterprises fall into the digital trap, that is, simple technology stacking fails to translate into a substantial improvement in supply chain risk resistance capabilities[6-7]. Through in-depth mechanism analysis and typical case verification, this paper provides operable implementation paths for the construction of digital resilience of manufacturing enterprises, helping enterprises solve transformation dilemmas and improve supply chain risk resistance capabilities.

2. Theoretical Foundation and Literature Evolution

2.1 Theoretical Origin of Supply Chain Resilience

The concept of resilience originally originated from materials science. Holling (1973) introduced it into the field of ecology and distinguished two core connotations: engineering resilience and ecological resilience. Engineering resilience focuses on the recovery speed of the system after impact, while ecological resilience focuses on the system's ability to absorb disturbances and maintain core functions. On the basis of ecological research, organization theory further puts forward the concept of evolutionary resilience, emphasizing that organizations achieve state transition and adaptive development through continuous learning. Ponomarev & Holcomb (2009) combined the operational characteristics of supply chains and defined supply chain resilience as the system's ability to prepare for, respond to and recover from disruption events. In recent years, the research focus of academia has gradually shifted to relational resilience and network resilience, paying more attention to the multi-agent collaborative linkage and adaptive capacity at the level of supply chain ecosystem, breaking through the research limitations of a single enterprise perspective [1,3].

2.2 Theoretical Integration of Digitalization and Supply Chain Management

The impact of digital technology on supply chain management has experienced a gradual evolution process. The first stage is the informatization stage, which relies on traditional information systems such as ERP and EDI to improve process operation efficiency, with transaction cost economics as the core theoretical support. The second stage is the digitalization stage, which shifts to data-driven refined decision-making, supported by the resource-based view and dynamic capability theory. The third stage is the digital-intelligence stage, where emerging technologies such as digital twin, artificial intelligence and blockchain have spawned a new theoretical research perspective. Among them, digital twin theory emphasizes the real-time mapping between physical supply chain and virtual model, realizing full-link operation visualization and optimal regulation. Platform ecosystem theory focuses on the reshaping effect of digital platform on supply chain power structure, promoting supply chain management from chain-dominant mode to platform coordination mode, providing diversified analytical tools for analyzing digital empowerment of supply chain resilience [8].

2.3 Research Evolution and Knowledge Gaps

Bibliometric analysis results show that the interdisciplinary research on digitalization and supply chain resilience presents obvious stage characteristics. Before 2010, relevant research mainly focused on the impact of supply chain information systems on operation efficiency, and the topic of supply chain resilience had not yet entered the mainstream of academic research. From 2011 to 2019, supply chain disruptions caused by natural disasters such as the Japanese earthquake

and Thai floods promoted an upsurge in supply chain resilience research, but digitalization was mostly regarded as a research background factor rather than a core explanatory variable. The COVID-19 pandemic in 2020 became a research watershed. The key role of digital technology in supply chain crisis response prompted academia to systematically examine the internal correlation between digitalization and supply chain resilience[3].

At present, there are still obvious knowledge gaps in relevant research. First, the existing research has too linear assumptions about the relationship between digitalization and supply chain resilience, ignoring the diminishing marginal effect of technology investment and the regulatory role of organizational adaptability. Second, insufficient consideration is given to industry context differences. Discrete manufacturing and process manufacturing, consumer goods manufacturing and industrial goods manufacturing may have significant differences in digital resilience construction paths, and relevant targeted research is scarce. Third, the theorization degree in the Chinese context is weak. The digital transformation of local enterprises has both institutional characteristics and industrial characteristics, making it difficult to directly apply Western mature theoretical frameworks for research [2,6,7].

3. Mechanism of Digitalization Enabling Supply Chain Resilience

Based on theoretical sorting and practical observation of manufacturing industry, this paper proposes three core mechanisms for digital empowerment of supply chain resilience in manufacturing industry, namely information transparency mechanism, intelligent decision-making mechanism and relationship coordination mechanism. The three mechanisms support and cooperate with each other to form a closed-loop system of "risk perception - intelligent decision-making - collaborative execution", comprehensively improving the level of supply chain resilience[4,6,7].

3.1 Information Transparency Mechanism: From Bullwhip Effect to Full-Link Visibility

The problem of information asymmetry within the supply chain has long restricted the improvement of operational efficiency and exacerbated supply chain vulnerability. Demand information is distorted and amplified step by step in the transmission process of upstream and downstream, forming a typical bullwhip effect, which leads to the coexistence of inventory backlog and stock-out risks. Digital technology breaks the dilemma of information asymmetry through three paths to achieve full-link transparency of the supply chain.

Real-time data collection layer. Relying on the deployment of internet of things, radio frequency identification, global positioning system and other technologies, enterprises can track material flow, production conditions and logistics status in real time, upgrading supply chain transparency from a single node level to a full-process level, laying a solid data foundation for early risk identification and accurate judgment[4].

Information integration platform layer. Cloud collaboration platform breaks internal and external information islands of enterprises, realizing real-time sharing of core data such as orders, inventory, logistics and production. The platform-based architecture supports many-to-many supply chain network collaboration, effectively reducing transaction costs between entities. Some leading enterprises have built a supply chain control tower model, integrating internal and external fragmented information through data middle platform to realize global visibility and unified management of the supply chain[7].

Risk mapping simulation layer. Digital twin technology maps the physical supply chain into a virtual simulation model, supporting dynamic simulation and deduction of various disruption scenarios. Enterprises can test different disturbance scenarios in a virtual environment, accurately evaluate the vulnerability of the supply chain network, optimize redundant resource allocation, realize predictive transparent management, and greatly improve the sensitivity and foresight of risk perception[9].

3.2 Intelligent Decision-Making Mechanism: From Empirical Judgment to Algorithm-Driven Decision-Making

The richness of data information does not necessarily lead to the optimization of decision-making quality; the core lies in transforming massive data into executable decision-making knowledge [4]. The iterative breakthrough of artificial intelligence technology promotes the transformation of supply chain decision-making mode from traditional empirical judgment to algorithm-driven intelligent decision-making, greatly improving the efficiency and accuracy of risk response. On the one hand, machine learning technology can process massive heterogeneous supply chain data, optimize the accuracy of demand forecasting models, help enterprises adjust capacity planning and inventory allocation in advance, and reduce operational risks caused by demand fluctuations [6-7]. Natural language processing technology can monitor external public information in real time, trace risk transmission paths and cascading impacts combined with knowledge graphs, and realize early warning and dynamic tracking of supply risks. On the other hand, reinforcement learning algorithms can quickly generate diversified alternative schemes when supply chain disruptions occur, including reallocating purchase

orders, adjusting logistics transportation routes, optimizing production scheduling plans, etc., significantly compressing risk response time and minimizing economic losses caused by disruptions.

3.3 Relational Collaboration Mechanism: From Transactional Game to Ecological Symbiosis

Supply chain resilience essentially depends on the overall coordination level of the network. Digital technology has profoundly reshaped the supply chain governance logic, promoting the transformation of subject relations from zero-sum transaction game to ecological symbiosis and win-win. The collaborative forecasting and replenishment mechanism supported by the cloud platform enables upstream and downstream enterprises to simultaneously carry out demand forecasting and production planning. Standardized API docking realizes the in-depth integration of supply chain subject systems, enhancing the relationship-specific investment and the ability to jointly respond to risks among subjects. The platform-based architecture effectively reduces the costs of multi-source procurement and supplier management, enabling enterprises to conveniently optimize supplier portfolios and cultivate backup supply resources. Some industry platforms launch the manufacturing capacity as a service model, building a cloud factory-style distributed elastic capacity network. Relying on distributed ledgers and smart contracts, blockchain technology further reduces information asymmetry between entities, reduces performance disputes and credit risks, replaces traditional relational trust with technical trust, and achieves a wider range of risk sharing and benefit sharing [10][8].

3.4 Mechanism Integration and Boundary Conditions

The above three mechanisms do not operate in isolation, but form an interconnected and organically linked whole. Information transparency is the core data basis for intelligent decision-making, decision-making quality directly affects supply chain collaboration efficiency, and collaboration depth in turn enriches information sources and optimizes decision-making application scenarios. At the same time, the digital empowerment effect is not automatically realized, and its implementation effect is doubly regulated by organizational capabilities and external institutional environment.

At the organizational level, the improvement of digital capabilities requires supporting process reengineering, professional talent cultivation and data culture transformation. Enterprises without a sound data governance system are prone to fall into the dilemma of rich data but poor information, and the level of digital leadership directly determines whether technical potential can be transformed into substantial resilience performance. At the level of supply chain power structure, if core enterprises strengthen unilateral control by virtue of data advantages, it will destroy the balance of collaborative ecology. Establishing a fair data sharing and value distribution mechanism is an important prerequisite for maintaining supply chain collaborative resilience. At the external environment level, data security regulations, industry technical standards and the perfection of digital infrastructure constitute rigid constraints. Restrictions on cross-border data circulation and inconsistent system interfaces will increase coordination costs and compliance risks for supply chain entities [5,8].

4. Empirical Evidence and Typical Cases

4.1 Main Findings of Quantitative Research

In recent years, scholars at home and abroad have conducted a large number of empirical studies on the correlation between digitalization and supply chain resilience, and the core research conclusions can be summarized into three levels.

At the macro level, the analysis results based on provincial panel data show that there is a significant positive correlation between the digital level of manufacturing industry and regional supply chain resilience, but this impact has an obvious threshold effect. When the digital level crosses a specific critical value, its marginal contribution to supply chain resilience gradually decreases, and even has a negative impact in the case of excessive digitalization, which is mainly due to the increase in supply chain system complexity and operation and maintenance costs.

At the micro level, empirical tests based on listed company data show that digital transformation of enterprises can significantly reduce revenue volatility and inventory turnover days, and improve performance stability in the face of industry downturn shocks. This positive effect is relatively weak in labor-intensive industries and small and medium-sized enterprises, confirming that there are industry heterogeneity and enterprise scale thresholds in digital resilience construction.

At the mechanism testing level, the mediating effect model verifies the mediating role of channels such as information integration, improved prediction accuracy and supplier diversification. The moderating effect analysis shows that environmental uncertainty including demand fluctuation and market competition intensity will strengthen the positive impact of digitalization on supply chain resilience, while institutional imperfections including weak intellectual property protection and difficult contract enforcement will weaken this positive effect [6-7].

4.2 Typical Case Analysis

4.2.1 Case 1: Haier Group: Resilient Ecosystem Driven by COSMOPlat Platform

The COSMOPlat industrial internet platform built by Haier has realized the advanced leap from internal digitalization of enterprises to industrial ecological digitalization. The platform connects hundreds of thousands of suppliers and millions of end users, building a full-process digital management system from user demand insight to product delivery. In terms of supply chain resilience construction, Haier's innovative practices are mainly reflected in three dimensions:

Modular design system: The high modularization of product architecture enables key components to be quickly switched between different suppliers, reducing the risk of single-source dependence[7].

Customer-to-Manufacturer (C2M): Through the pre-sale model and flexible production lines, inventory pressure is moved forward to the user side, greatly reducing inventory risks caused by demand forecasting errors[4,6].

Ecological capacity scheduling: Numerous small and medium-sized manufacturers connected to the platform form a distributed capacity reserve, which can be quickly activated in peak demand or sudden disruptions [8].

4.2.2 Case 2: Midea Group: Channel Digitalization under T+3 Model

Midea Group's digital transformation takes channel reform as a breakthrough, building a unique supply chain resilience mechanism:

Order-based production: Changing the traditional inventory-pressing model, production planning is driven by terminal sales data, reducing the channel inventory cycle from 60 days to less than 30 days, lowering the risk of inventory backlog [4].

Supplier collaboration platform: Core suppliers are connected to Midea's system to share production plans and inventory data, realizing just-in-time supply of raw materials (JIT). At the same time, through platform-based quality data tracing, supply quality problems can be quickly located and solved[6].

Multi-regional capacity layout: Relying on the unified scheduling of digital systems, Midea's multiple manufacturing bases at home and abroad can dynamically adjust capacity allocation according to regional risk conditions, enhancing the resilience benefits brought by geographical dispersion [7].

4.3 Practical Insights and Implementation Difficulties

The above cases of leading enterprises reveal the common laws of digital resilience construction. Successful digital transformation is by no means a simple technology deployment, but a systematic reform of business model, organizational capability and technology system. At the same time, manufacturing enterprises still face many practical challenges in the process of practice. On the one hand, the initial investment in digital infrastructure is large, and the benefits of supply chain resilience are long-term implicit values, which are difficult to be directly reflected in conventional financial accounting, leading to insufficient willingness of some enterprises to invest in transformation. On the other hand, the uneven quality of enterprise historical data and the persistent internal information islands greatly limit the application scenarios and implementation effects of digital technologies. In addition, in the process of multi-stakeholder coordination of the supply chain, concerns about trade secret protection, transformation investment allocation and unification of technical standards further increase the difficulty of industrial ecological collaboration.

5. Practical Paths and Policy Recommendations

5.1 Phased Implementation Paths at the Enterprise Level

Based on the law of capability evolution and risk control requirements, manufacturing enterprises can adopt a three-stage promotion strategy:

Foundation Consolidation Period (1-2 years). This stage focuses on promoting the digital transformation of internal processes and improving data basic governance. The core tasks include integrating and connecting core operation systems such as ERP, MES and WMS, deploying internet of things infrastructure and establishing standardized data collection specifications, and building a full-process data quality management system. At this stage, blind pursuit of advanced technology applications should be avoided, focusing on the accumulation of data assets and the improvement of internal collaboration efficiency.

Capability Expansion Period (2-3 years). The focus of this stage shifts to the digital connection of upstream and downstream supply chains and the construction of intelligent decision-making capabilities. Key measures include building a supplier collaboration platform and realizing system docking with core partners, implementing artificial intelligence application scenarios such as demand forecasting and inventory optimization, and establishing a sound supply chain risk monitoring and early warning mechanism. At this stage, change management should be strengthened, a data-driven decision-making culture should be cultivated, and the digital literacy of all employees should be improved.

Ecological Optimization Period (3-5 years). The goal of this stage is to integrate into or lead the industrial digital ecosystem and build networked resilience capabilities. The development directions include participating in or building an industrial-level supply chain platform, deepening the application of digital twin technology in supply chain planning, and cultivating a diversified supplier network and flexible capacity system. At this stage, the strategic focus shifts from simple efficiency optimization to risk governance and industrial value co-creation [5].

5.2 Ecological Cultivation at the Industrial Level

The industrial level needs to focus on ecological collaboration and solve the shortcomings of digital transformation of small and medium-sized enterprises. Support leading enterprises in the industry to open their own digital platforms as industrial public infrastructure, provide low-cost, lightweight digital tools for small and medium-sized enterprises, and ensure the neutrality and openness of platform operation. In view of the resource constraints of small and medium-sized enterprises, promote lightweight, subscription-based software-as-a-service solutions, and drive upstream and downstream enterprises to simultaneously promote digital transformation relying on the order traction of chain-leading enterprises.

At the same time, relying on the real transaction data deposited on the industrial platform, develop data-driven supply chain financial services, alleviate the financing constraints of small and medium-sized enterprises through digital accounts receivable, dynamic inventory monitoring and other models, and improve the overall financial resilience of the supply chain network. Establish an industry digital transformation alliance to promote the sharing of technical experience, coordinated formulation of standards, and reduce the transformation cost of the entire industrial chain [10].

5.3 Institutional Supply at the Policy Level

The policy level needs to improve the institutional guarantee system and create a favorable environment for digital transformation. Accelerate the improvement of data factor market rules, clarify the ownership of supply chain data property rights, circulation transaction rules and security guarantee mechanisms, establish a data sharing incentive mechanism, and promote the orderly opening of industrial public data. Relying on the industrial internet and national logistics platform system, build a risk monitoring and early warning system for key industrial chains, implement real-time tracking and management for key industries and key materials, and launch a cross-departmental and cross-regional coordination mechanism when major risks occur.

In addition, strengthen the training of digital composite talents, add supply chain digital-related courses in higher education and vocational education systems, and make up for the shortcomings of talent supply. Unify supply chain digital interfaces and data format standards to reduce enterprise system docking costs and technical barriers. Increase support for the research and development of key core digital technologies, break through technical bottlenecks such as industrial software and high-end sensors, and consolidate the technical foundation for digital transformation of manufacturing industry[5].

6. Conclusion and Prospect

This paper systematically explains the theoretical logic and practical path of digital empowerment for supply chain resilience of manufacturing enterprises, constructs a triple mechanism of "information transparency - intelligent decision-making - relationship coordination", and reveals the internal mechanism of digitalization enhancing resilience by breaking information asymmetry, improving risk response speed and reshaping supply chain governance model. Empirical analysis and case study results show that the impact of digitalization on supply chain resilience presents non-linear characteristics, with significant threshold effect and context dependence. The practical experience of Haier COSMOplat platform and Midea T+3 model further confirms the importance of coupled development of technical capabilities, organizational change and ecological collaboration. This paper suggests that enterprises adopt a three-stage implementation path of foundation consolidation - capability expansion - ecological optimization, avoid blind technology-oriented investment, and realize the in-depth integration of digitalization and resilience construction.

Future research can be further deepened from three directions. First, carry out cross-industry comparative research to explore the differentiated laws of digital resilience construction paths between discrete manufacturing and process manufacturing, consumer goods and industrial goods manufacturing, and refine industry-specific research. Second, introduce the perspective of evolutionary economics to track the dynamic evolution process and path dependence characteristics of digital resilience, and reveal long-term evolution laws. Third, strengthen theoretical construction in the Chinese context, integrate institutional environment, industrial policy and local relationship governance into the analysis framework, extract theoretical results in line with the actual development of China's manufacturing industry, and contribute Chinese experience to global supply chain resilience research.

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