

Analyzing the Implementation Pathways of Blockchain Technology-Enabled Supply Chain Resilience in the Manufacturing Industry

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Abstract. Against the backdrop of escalating geopolitical conflicts, public health crises, and demand volatility, manufacturing supply chains face mounting disruption risks, while traditional management approaches exhibit persistent limitations in information transparency, trust building, and coordinated response. Existing research has largely focused on isolated applications and lacks a comprehensive analysis of the mechanism linking technical characteristics, intermediary capabilities, and supply chain resilience. This study examines how blockchain technology enables supply chain resilience in the manufacturing sector through a systematic literature review and theoretical analysis, supplemented by illustrative industry cases. Drawing on empirical and analytical studies published between 2018 and 2026, the paper identifies three core implementation pathways: enhanced information transparency and real-time sharing to strengthen predictive and adaptive capacity; smart-contract-enabled collaboration to improve cross-organizational coordination; and end-to-end traceability to strengthen risk management and accelerate recovery. Cases such as BMW's PartChain initiative and Walmart's blockchain traceability system demonstrate these pathways in practice. The analysis further reveals that blockchain effectiveness is contingent on capacity level and demand uncertainty. Deployment costs, interoperability gaps, and data privacy concerns constrain broader adoption. The study concludes with targeted countermeasures for firms, industry consortia and regulatory authorities, alongside suggestions for future research directions.

Keywords: blockchain technology, supply chain resilience, manufacturing industry, smart contracts, implementation pathways, case study

1. Introduction

In recent years, global manufacturing supply chains have faced unprecedented levels of uncertainty. Geopolitical tensions, the COVID-19 pandemic, frequent natural disasters, and volatile demand have combined to transform supply chain disruptions from occasional events into pervasive risks. Traditional supply chain management, characterized by linear hierarchical structures and independently operating node systems, suffers from information silos, data asymmetry, and delayed responses—structural deficiencies that hinder effective anticipation, rapid coordination, and efficient

recovery in complex and dynamic environments [1]. Consequently, supply chain resilience has become a central concern for both scholars and practitioners. Meanwhile, digital technologies represented by blockchain offer new momentum for supply chain management transformation within the broader Industry 4.0 paradigm [2]. Blockchain enables decentralized storage and transparent information sharing through distributed ledgers, automatic execution of contractual terms via smart contracts, and data immutability through hash-chained structures and timestamps [3]. These features align closely with supply chain resilience requirements for transparency, coordination efficiency, and rapid risk response [4]. However, existing research has largely focused on fragmented blockchain applications in specific scenarios, such as product provenance and financial transactions, while a systematic explanation of the mechanisms through which blockchain can enhance resilience in manufacturing supply chains remains limited. Few studies have adopted a "technology characteristic—capability intermediary—resilience dimension" logic, integrated with empirical cases, to reveal the specific pathways and boundary conditions of blockchain-enabled resilience.

This study systematically analyzes the implementation pathways and mechanisms through which blockchain can enhance resilience in manufacturing supply chains, drawing on empirical findings and illustrative industry cases. The core questions are: Through which pathways does blockchain improve manufacturing supply chain resilience? Which resilience dimensions does each target? And what contextual factors moderate the effect? The paper employs literature review and theoretical analysis, retrieving studies from Web of Science, CNKI, and IEEE Xplore (2018-2026), and integrating empirical findings, analytical results, and industry cases. Theoretically, it enriches the digital technology—supply chain management framework; practically, it helps manufacturing firms identify blockchain value entry points and deployment strategies.

2. Core concepts and theoretical foundation

Supply chain resilience is generally conceptualized as a multi-dimensional capability encompassing prediction, adaptation, and recovery. Prediction refers to the ability to foresee potential disruptions through environmental scanning and data analytics; adaptation denotes the capacity to adjust operations and reconfigure resources during a disruption; recovery describes the speed and effectiveness with which the supply chain restores normal performance or transitions to an improved state after a shock [1]. Manufacturing supply chains possess distinctive characteristics that amplify the importance of resilience: tight capacity constraints mean that production cannot be readily scaled; long, multi-tier chains require coordination across numerous independent actors; and high disruption costs—including lost revenue, contractual penalties, and reputational damage—make slow recovery particularly damaging. These characteristics make manufacturing supply chains more vulnerable to cascading failures and increase the need for proactive resilience building. Unlike general service or retail supply chains, manufacturing systems rely heavily on synchronized material flows across tier-1 suppliers, component assemblers and final distribution networks, where even a minor disruption in a single upstream node can propagate rapidly through the entire chain, making the three-dimensional resilience framework a non-negotiable operational requirement rather than an optional strategic advantage.

Three technical features of blockchain are particularly relevant to supply chain resilience. First, the distributed ledger enables decentralized, synchronized record-keeping across all authorized nodes, eliminating single points of failure and ensuring that every participant accesses an identical, real-time version of transactional data [3]. Second, smart contracts are self-executing programs encoded with predefined contractual rules; when specified conditions are met, contractual

obligations—such as payments, order confirmations, or capacity allocations—are executed automatically without intermediary intervention [5]. Third, hash-chained data structures and timestamping mechanisms make unauthorized retroactive alteration of records difficult, thereby providing an auditable and tamper-resistant record of products, transactions, and processes from origin to end consumer.

The theoretical alignment between blockchain and supply chain resilience lies in the technology's capacity to address the root causes of supply chain vulnerability—information asymmetry and coordination friction. Traditional supply chains operate on an "information asymmetry" paradigm in which each node holds partial, often delayed data, leading to suboptimal decisions and the bullwhip effect. Blockchain can shift this paradigm toward greater transparency and collaboration by providing a shared and trustworthy data layer. This reduces the need for costly verification and reconciliation and enables supply chain partners to make more coordinated decisions based on a common information base [6]. This paradigm transition directly supports the three resilience dimensions: transparency improves prediction, automated coordination enhances adaptation, and immutability accelerates recovery.

3. Implementation pathways of blockchain-enabled manufacturing supply chain resilience

3.1. Pathway one: information transparency and real-time sharing—strengthening prediction and adaptive capacity

Blockchain improves supply chain resilience by dismantling information silos and enabling real-time data synchronization across supply chain nodes. Its distributed ledger grants authorized participants simultaneous visibility into demand signals, inventory status and production updates, lowering information latency and distortion prevalent within multi-tier manufacturing supply chains. Enhanced visibility mitigates the bullwhip effect, whereby order volatility amplifies moving upstream. The first pathway through which blockchain enhances resilience is by breaking information silos and enabling real-time data synchronization across supply chain nodes. The distributed ledger ensures that demand signals, inventory levels, and production status are visible to all authorized participants simultaneously, reducing the information latency and distortion that characterize traditional multi-tier supply chains. This improved visibility directly mitigates the bullwhip effect, in which order variability amplifies upstream. Srivastava et al., based on a survey of 389 supply chain professionals, found that blockchain adoption significantly improved perceived usefulness and attitudes toward information sharing, supporting its potential role in reducing demand distortion [7]. Similarly, simulation-based research on Industry 4.0 supply chains demonstrates that blockchain integration yields a significant reduction in order variance ratios across all tiers, confirming its capacity to dampen the bullwhip effect.

A prominent industry case is BMW Group's PartChain initiative, launched in 2020 with supplier Marelli. Built on Hyperledger Fabric, PartChain creates a permissioned consortium chain connecting Tier-1 suppliers, logistics providers, and BMW's internal systems, enabling real-time sharing of component production data, shipment status, and quality certificates across the global automotive network. The pilot initially covered headlamp and rear-lamp traceability across three Marelli plants, indicating that synchronized data access could reduce the time required to verify supplier production status and adjust production schedules. By making demand and capacity data visible in real time, PartChain illustrates how distributed ledger technology transforms fragmented information flows into a shared visibility layer—directly strengthening the predictive and adaptive dimensions of resilience.

Empirical evidence further indicates that the value of blockchain-enabled information sharing is context-dependent. Wu and Li, through an analytical model of two competing manufacturers under demand uncertainty, demonstrate that blockchain-enabled information sharing is preferred when capacity levels are high: with abundant capacity, the primary challenge is demand forecasting, and real-time visibility allows manufacturers to optimize production planning. In a food industry study combining survey data and system dynamics [8], Vu et al. found that blockchain adoption had immediate effects on inventory levels and lead times and reduced costs over the longer term, supporting the operational benefits of transparent information sharing [9].

3.2. Pathway two: smart contracts and collaborative efficiency—enhancing coordinated response capacity

The second pathway leverages smart contracts to automate and enforce cross-organizational collaboration, thereby enhancing the supply chain's coordinated response capacity during disruptions. In traditional supply chains, capacity sharing and mutual aid agreements often rely on ex post negotiation, which can be slow and costly and may be vulnerable to opportunistic behavior. Smart contracts convert collaborative arrangements into ex ante programmed rules: when predefined trigger conditions occur—such as a manufacturer's capacity falling below a threshold—the contract automatically executes capacity reallocation, order rerouting, or payment transfers without lengthy negotiation [5]. This shifts coordination from a reactive, dispute-prone model to a proactive, trust-minimized model. Wu and Li provide critical analytical evidence for the conditional value of this pathway [8]. Their model shows that blockchain-enabled capacity sharing is preferred over information sharing when capacity levels are moderate and demand uncertainty is not extremely low: under these conditions, the binding constraint is insufficient supply rather than poor forecasting, and automated capacity sharing allows manufacturers to pool resources and improve service levels. The study also finds that ex ante cooperation through smart contracts can achieve greater efficiency than ex post negotiation, because it secures capacity commitments before demand is realized and helps mitigate hold-up problems.

From an empirical standpoint, Dou et al., using structural equation modeling on survey data from 251 Chinese manufacturing firms, demonstrate that blockchain technology significantly enhances supply chain resilience and relationship performance by fostering relational trust and network capability among supply chain partners [10]. This finding suggests that collaboration enabled by smart contracts can improve operational efficiency while also strengthening inter-organizational trust, which underpins resilient supply networks. A related study of 212 Chinese manufacturing firms further shows that blockchain adoption significantly enhances relational governance and resource orchestration, which in turn strengthen circular supply chain resilience.

3.3. Pathway three: full-process traceability and risk management—improving recovery capacity

The third pathway involves blockchain's immutable, timestamped record of product flows, which enables end-to-end traceability across the product lifecycle. When a disruption occurs—whether a quality defect, supplier failure, or logistics bottleneck—blockchain records allow firms to rapidly pinpoint the source and scope of the problem, thereby shortening response times and reducing the costs associated with product recalls, compliance breaches, and fraud. The most widely cited demonstration of this pathway is Walmart's blockchain traceability system, developed with IBM. In a pilot test, the time required to trace a package of mangoes from store shelf back to the originating

farm was reduced from approximately seven days to 2.2 seconds—an efficiency improvement of over 99.99 percent. Although Walmart operates in retail rather than manufacturing, this case vividly illustrates the recovery-capacity potential of immutable traceability, and the same principle applies to manufacturing component recall and defect localization.

In the manufacturing sector, BMW's PartChain extends traceability beyond logistics to component-level provenance: each module carries a unique digital identity linking raw material batches, assembly parameters, inspection results, and shipment events. When a quality issue arises, BMW can identify precisely which vehicles contain the affected component within minutes, replacing broad recalls with targeted interventions. Empirical data from Chinese manufacturing quality traceability systems further corroborate this pathway: a blockchain-based platform reduced nonconforming-product tracing time from 48 hours to 1.8 hours (a 96.25% improvement), shortened supplier response from 8 to 3.6 hours, and lowered collaborative dispute rates from 35% to 8%. Qualitative research based on grounded theory further identifies multiple empirically observed resilience patterns in manufacturing, including internal-environment-driven and blockchain-enabled internal-external coordination models. A systematic review of post-2020 blockchain applications confirms that traceability, compliance, security, and fraud prevention are among the most consistently reported resilience impacts, with smart contracts and distributed ledgers as dominant mechanisms [11].

4. Barriers, challenges and countermeasures

Despite the demonstrated potential of blockchain, several barriers constrain its large-scale adoption in manufacturing supply chains. First, high deployment costs—including infrastructure, system integration, and maintenance—place a disproportionate burden on small and medium-sized enterprises, which may limit participation among smaller firms and weaken network effects. A systematic review identifies adoption and organizational barriers as the most cited obstacles (28.3%), followed by technical limitations (26.1%) and interoperability and standards issues (21.7%). Second, cross-organizational system compatibility remains inadequate: many firms operate legacy ERP systems that do not readily interface with blockchain platforms, and the absence of unified data schemas complicates integration [11]. Even BMW's PartChain required extensive custom integration between Hyperledger Fabric and suppliers' disparate systems. Third, data privacy and commercial confidentiality concerns deter firms from sharing sensitive operational data on a distributed ledger, because the transparency that enables resilience also risks exposing proprietary information.

To address these barriers, three strategies are recommended. First, firms should adopt a phased implementation approach, beginning with high-value, low-complexity applications such as product provenance and document digitization, and then progressively expanding into more complex use cases, such as smart-contract-based capacity sharing, as their technical capabilities and inter-organizational trust develop. BMW's PartChain exemplifies this approach, starting with a single component category (automotive lighting) before scaling to additional parts. Second, industry consortium chains should be promoted: by pooling resources, sharing infrastructure costs, and co-developing technical standards, consortium models reduce individual financial burden and address interoperability gaps while preserving data access controls. Third, regulators and industry bodies should establish clear legal frameworks that define data ownership, liability, and the legal validity of smart contracts, and should encourage privacy-enhancing technologies such as zero-knowledge proofs and off-chain storage with on-chain hashes to reconcile transparency with confidentiality.

These measures collectively create an ecosystem in which blockchain's resilience benefits can be realized without exposing firms to undue cost or risk.

5. Conclusion

Three interrelated pathways are identified: information transparency and real-time sharing (illustrated by BMW PartChain's real-time supplier data synchronization); smart-contract-driven collaborative efficiency (supported by Wu and Li's capacity-sharing model and Dou et al.'s survey of 251 firms); and full-process traceability (demonstrated by Walmart's 7-day-to-2.2-second traceability reduction and Chinese manufacturing quality systems). Together they constitute a full-cycle resilience system spanning ex ante anticipation, in-process coordination, and ex post recovery. The effect of blockchain is context-dependent: high capacity favors information sharing, while moderate capacity with demand uncertainty maximizes capacity-sharing value. This study is limited by its reliance on literature review and theoretical analysis and the absence of primary empirical validation. Future research could employ multi-case studies or large-scale questionnaire surveys to empirically test the boundary conditions of blockchain-enabled resilience across different industries, firm sizes, and development stages. Additionally, future work may explore how the integration of blockchain with artificial intelligence and the Internet of Things can synergistically amplify supply chain resilience effects.

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