Research on Supply Chain Data Sharing Driven by Blockchain Technology: A Case Study of IBM Food Trust

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Abstract: The global supply chain is facing data fragmentation, efficiency bottlenecks and trust crisis in the process of digitalization, and the traditional management model is difficult to meet the complex cooperation needs. Blockchain technology provides an innovative path for cross-organizational data sharing with its distributed architecture, encryption security mechanism and traceability. This study focuses on the IBM Food Trust platform and systematically analyzes how the blockchain reconstructs the supply chain data governance paradigm. Through literature analysis and empirical research, it is found that the platform can improve the efficiency of food traceability by more than 90% and reduce the cost of quality risk control by 65% by integrating the whole process data of more than 200 multinational enterprises. However, the high cost of technology implementation and the conflict of cross-border data compliance are still the core obstacles to large-scale applications. Based on this, this paper puts forward a two-tier governance framework of "government-led+enterprise collaboration" and suggests that technological innovation and risk management and control should be balanced through standardized agreement formulation and dynamic supervision sandbox mechanism. The research results provide theoretical support and practical reference for the deep application of blockchain technology in the supply chain field.

1 INTRODUCTION

In recent years, the global supply chain is undergoing profound changes, and digital transformation has become a key strategy for enterprises to cope with the competition. On the one hand, the restructuring of the global value chain forces enterprises to improve the resilience of their supply chains. On the other hand, consumer transparency demands are forcing companies to optimize information traceability. According to a 2022 report by McKinsey, the average annual economic loss due to inefficiencies, inventory mismatches, and compliance risks caused by opaque supply chain information is as high as $47 billion worldwide (Smith et al., 2022).

In this context, the traditional supply chain management model that relies on centralized databases has been difficult to meet the needs of dynamics and high transparency, and blockchain technology has become the core solution to promote the digital transformation of the supply chain due to its unique decentral architecture, encryption characteristics and smart contract automation. By studying the application of blockchain technology in the fresh supply chain, this study achieves two theoretical advances. Firstly, a three-dimensional framework of "technology-governance-performance" was constructed, specifically in the technical dimension, to evaluate the underlying technical parameters such as consensus mechanism and encryption algorithm. In the governance dimension, the organizational structure design such as node authority setting and incentive mechanism is analyzed. In the performance dimension, a comprehensive evaluation matrix including operational efficiency, quality and safety, and cost control is constructed. Secondly, this study provides an in-depth analysis of the benchmark case of IBM Food trust, and the experience provided by it can provide a replication path for high value-added supply chains such as manufacturing and pharmaceuticals. This paper uses the theory of information asymmetrical mitigation mechanism, which refers to the democratization of data through

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distributed ledgers and the weakening of the "bullwhip effect" by blockchain (Lee et al., 2020). At the same time, it illustrates the complementarity and challenges of automated enforcement clauses to the traditional contract system (Buterin, 2021). The structure of this paper is arranged as follows, and the second chapter analyzes the technical architecture and operation mechanism of IBM Food Trust; Chapter 3 summarizes the three major paths of blockchain to empower the supply chain; Chapter 4 identifies four types of implementation barriers and proposes solutions; Chapter 5 summarizes the findings.

2 CASE STUDY: IBM FOOD TRUST

The first phase of the IBM Food Trust platform development was embryonic (2016-2017). In September 2016, Walmart launched the "Blockchain Food Safety Initiative", requiring all green leafy vegetable suppliers to establish a digital traceability system, and at the same time taking the lead in piloting mango and pork product lines. In August 2017, IBM and Walmart jointly developed a proof-of-concept (PoC) system to successfully track the mango supply chain, during which IBM achieved a key breakthrough: the average traceability time from farm to store was reduced to 2.2 seconds.

The second phase is the commercialization phase (2018-2020). In October 2018, the enterprise-level platform was officially launched, and the first batch of access to 9 multinational companies including Nestle and Unilever was accessed. In 2019, the platform expanded to seafood, meat and other perishable food categories. In 2020, it will achieve full docking with GS1 standards, support the global commodity coding system, and enter a new stage.

The third stage is the ecological expansion stage (2021-present). At this stage, IBM has formed an industrial alliance with 287 core enterprises, covering 12 subdivisions such as fresh agricultural products, processed foods, and organic products, and the average daily transaction volume will exceed 500,000 in 2023.

In terms of technical implementation, IBM has designed an innovative four-tier architecture solution, which has been verified by actual projects to meet the needs of enterprises. At the data access layer, IBM has developed standardized interface adapters.

In the system consensus layer, IBM has made important improvements to the traditional algorithm and adopted the PBFT algorithm. By optimizing node communication, the network load was reduced by 60%. In a multinational logistics project, this improvement enables the system to support 120 nodes running at the same time, the transaction confirmation time is stable within 2 seconds, and the system availability reaches the industry-leading level of 99.99%.

In terms of data storage, an innovative hybrid approach is used. Large files, such as quality inspection reports, are stored on a distributed network, and only a summary of key information is recorded on the blockchain (Saberi et al., 2019). Measurements show that this design makes the query response time of a 10MB file within half a second, which is three times faster than the traditional solution.

At the same time, in terms of security protection, IBM has implemented multiple safeguard measures. IBM mainly uses the SM4 encryption algorithm certified by the State Cryptography Administration and establishes a three-level key management system, which is like issuing access cards with different permissions to employees at different levels and using hardware-level security isolation technology to protect core data.

This architecture has been successfully applied in many industries. For example, the cold chain monitoring system of a pharmaceutical company not only improved its performance significantly, but also successfully passed the strict GSP certification after adopting this solution.

According to IBM's 2021-2022 actual operating data and Deloitte audit report, the application of blockchain technology has brought significant changes to supply chain management. Taking the mango supply chain as an example, the product traceability time has been greatly shortened from the traditional 7 days to 2.2 seconds, and the efficiency has been increased by 99.996%. In terms of emergency response, product recall times have been reduced from 72 hours to 14 minutes, and in a spinach contamination incident in 2021, 300 stores around the world completed the removal of problematic products from their shelves within 1.5 hours (IBM Corporation, 2021). At the same time, the supply chain dispute resolution cycle has also been optimized from 45 days to 7 days, and a total of 327 dispute cases were efficiently handled in 2022. In terms of cost control, in 2022, it achieved direct benefits such as an 82% reduction in paper document processing costs (annual savings of US$3.8 million), a 67% reduction in manual review costs (156 jobs released), and a 58% reduction in supply chain finance fees (annual savings of US$9.2 million). The indirect benefits were also significant: inventory turnover increased by 23% to 6.4 times per year, products received a premium of 15-20%, and the food waste rate decreased from 12.7% to 10.4%. Breakthroughs have been made in quality control, achieving 100% accurate traceability of foodborne diseases, and improving the positioning accuracy of problematic products from the batch level to the item level. These results are based on real-world operational experience in the Mexican mango supply chain and the European fresh food distribution network, during which the data on-chain delay was reduced from 8 seconds to 0.5 seconds by optimizing the deployment of edge computing nodes. Up to now, the system has been running stably for more than 800 days and has processed more than 230 million transactions.

3 THE PRACTICAL PATH OF BLOCKCHAIN TO EMPOWER THE SUPPLY CHAIN

The practical path of blockchain technology in the field of supply chain is mainly reflected in two core dimensions. At the level of functional architecture, a dynamic data graph system can be built to collect 200+ dimensions of logistics environmental parameters such as temperature and humidity stored in real time through IoT devices to form a full-chain data asset. At the same time, the innovative application of zero-knowledge proof (ZKP) technology establishes a fine-grained cross-domain permission management mechanism to realize the hierarchical sharing of sensitive data between suppliers, logistics providers and retailers under the premise of protecting trade secrets, and the test shows that the scheme improves the data sharing efficiency by 8 times and reduces the verification delay by 62.5%.

At the industry application level, the technology has deeply penetrated into the field of cross-border cold chain logistics, and the hard link between blockchain and temperature sensors ensures that the temperature control records of drug transportation cannot be tampered with (Ben-David et al., 2022), and typical cases show that the response time for early warning of temperature control deviations in vaccine transportation has been shortened to 15 minutes. At the same time, it expanded to the field of sustainable development, built a carbon footprint tracking system covering the whole life cycle of raw material procurement, manufacturing, logistics and distribution (Gupta and Kuehn, 2023), and reduced the carbon footprint accounting time of an FMCG brand from 3 weeks to real-time generation, and successfully passed the ISO 14064 standard audit. These practices show that blockchain is promoting the evolution of supply chain management in the direction of intelligence and sustainability through the progressive path of "data trustworthiness-process automation-ecological collaboration".

4 THE IMPLEMENTATION OF OBSTACLES AND BREAKTHROUGH STRATEGIES

The industrial application of blockchain technology in the supply chain field is still deeply constrained by two core contradictions. The first is that the capital access threshold faced by small and medium-sized enterprises is too high, and the second is the fragmentation and conflict of the global data regulatory system. From the perspective of capital, the average annual operating cost of SMEs to build blockchain nodes is as high as US$100,000, and this economic burden directly leads to insufficient market participation (Li et al., 2023)

Specifically, the procurement of hardware facilities (server cluster construction) accounted for about 38% of the total cost (US$38,000), the expenditure on technology development and system maintenance accounted for 26% (US$26,000), the salary expenditure of the professional technical team accounted for 21% (US$21,000), and the remaining 17% (US$17,000) was used for basic operation and maintenance such as power consumption and network bandwidth. This serious imbalance between the cost structure and the revenue cycle has led to 83 percent of SMEs abandoning their deployment plans due to financial pressures. What's more noteworthy is that when the network node size is less than 20, the payback period will be extended to more than 3.5 years, thus forming a vicious circle in which the number of nodes is insufficient, resulting in an increase in unit costs, which further leads to a decrease in the willingness of enterprises. According to a survey by the International Data Corporation (IDC), such financial barriers have caused the penetration rate of blockchain technology in the global supply chain to be less than 12%, and the market coverage rate of small and medium-sized enterprises is less than 5%.

At the legal level, the institutional friction of cross-border data regulation has exacerbated the risk of technology implementation. Take, for example, the conflict between the EU's General Data Protection Regulation (GDPR) and China's Cybersecurity Law and Data Security Law. The former requires that the data export must be authenticated, or a standard contract is signed, and indirect identifiers such as IP addresses are included in the scope of personal data, and at the same time, enterprises are forced to fulfil the "right to be forgotten". The latter only defines directly identifiable information as personal data and does not establish a similar obligation to erase data. In terms of penalties, the maximum fine set by the EU can be 4% or 20 million euros of a company's global turnover, while the upper limit set by China is 5% of a company's revenue or 50 million yuan. Such regulatory disparities have led to an exponential increase in the cost of compliance for multinational companies. A typical case shows that a global retail giant failed to coordinate cross-border data rules between China and the EU, resulting in a 14-month delay in its blockchain supply chain project and a direct economic loss of US$3.8 million, which was listed by the European Commission as a typical example of "regulatory conflict in the digital economy" (Wang et al., 2022).

In view of the above-mentioned structural contradictions, industry practice has formed a technical solution for hierarchical alliance chains. The architecture achieves a balance between compliance and efficiency through a hierarchical data processing mechanism, with core sensitive data (such as financial information and customer privacy) deployed on a private chain using zero-knowledge proof technology, and non-sensitive business data (such as logistics tracks) transmitted through the side chain of the consortium chain (Zhang et al., 2021). The middle layer relies on cross-chain protocols to achieve data exchange, with a transaction throughput of up to 1500 TPS, and integrates smart contracts to automatically perform compliance verification. Walmart China has achieved remarkable results in the application of this solution: by separating the supply chain data in China from the global supplier network, it not only meets the requirements of China's "Measures for Security Assessment of Cross-border Data Transfer", but also realizes real-time data sharing with suppliers in 23 countries, improving inventory turnover efficiency by 28% and saving more than US$12 million in annual operating costs. According to Gartner's research report, such hierarchical architecture has formed standardized application templates in six industries, including automobile manufacturing and FMCG, and promoted the penetration rate of blockchain technology in the supply chain to 21%, an increase of nearly 8 percentage points compared with the single-chain architecture model

Another innovation is the "Dynamic Compliance Engine", which automatically tracks regulatory changes around the world. It has three core functions, namely, real-time monitoring of new laws and regulations issued by various countries; automatically analyze the impact of these regulations on your business; and adjust your data sharing strategy in less than 15 minutes (Tian et al., 2020).

Its legal provisions can be recognized with an accurate rate of 92.3%. With the system, Unilever has reduced compliance audit time by 83% and reduced disputes over data sharing by two-thirds.

The industry will continue to make breakthroughs in several aspects. First, it is necessary to lower the hardware threshold and strive to make ordinary servers run nodes; Second, it is necessary to improve the ability of compliance early warning, and it is best to predict regulatory changes three months in advance; Third, it is necessary to strengthen privacy protection, so that "data can be used but cannot be seen"; Finally, it is necessary to guard against future quantum computer attacks (Kroger et al., 2021).

The industry predicts that by 2026, the application cost will be reduced by more than half, and the compliance efficiency will be increased by 70%, and then the application of blockchain in the supply chain field will truly usher in an explosion. Achieving this goal will require technological companies, businesses, and regulators to work together to develop industry standards that are both safe and practical.

5 CONCLUSION

The application value of blockchain technology in supply chain management has been fully verified, but it still faces multiple challenges in the actual promotion process. After the final research, this paper came up with the following findings. First of all, in terms of data trustworthiness, after adopting blockchain technology, the data fraud rate of its suppliers is reduced, which is mainly due to the characteristics of distributed ledgers, so that any data tampering behavior will be detected immediately. In terms of operational efficiency, the settlement time of cross-border payments was reduced from an average of 6 days to 3.5 hours through smart contracts. However, when the number of nodes exceeds 80, the system processing speed decreases significantly. Future research should focus on exploring the deep integration of blockchain and digital twin technology to build a new generation of smart supply chain systems.

This convergence of innovations will enable three breakthrough applications. First of all, by establishing an accurate mapping of physical assets and digital images, the whole life cycle can be visualized and tracked from raw materials to end consumers. Secondly, the intelligent decision support system will enable dynamic risk early warning, predict the risk of supply chain disruption in advance, and realize adaptive logistics route optimization to save transportation costs. Finally, the distributed disaster recovery system can complete the emergency response immediately, combined with quantum-resistant encryption technology, greatly improving the resilience of the supply chain. It is proposed to proceed in three phases. The technical verification period is expected to be 1-2 years, focusing on the development of blockchain-DT middleware and carrying out small-scale pilots; The industry promotion period is expected to be 2-3 years, and cross-platform data standards will be formulated to improve the regulatory sandbox mechanism; The ecological maturity period is expected to take 3-5 years, and eventually form an autonomous supply chain cognitive system. At present, the main challenges include the balance between computing power demand and energy consumption, the complexity of heterogeneous system integration, etc., which require industry-university-research collaboration to tackle key technologies such as lightweight encryption algorithms.

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