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Study on the Coordination Mechanism of Blockchain-Based Cross-Chain Traceability Systems for Food Supply Chains

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Abstract: Addressing the issues of insufficient information sharing and low coordination efficiency in food supply chain cross-chain traceability, this study proposes a coordination mechanism based on blockchain technology. We innovatively construct a Stackelberg game model consisting of a "pork supply chain" (upstream) and a "frozen dumpling supply chain" (downstream). By introducing the concept of the "cost threshold effect," we quantify the critical conditions for investment in blockchain technology and propose, for the first time, a "Blockchain Technology Investment Decision Matrix" to define the technical adaptation boundaries under various cost-preference combinations. Numerical simulations validate the effectiveness of blockchain in reducing inventory costs for the upstream supply chain and expanding the potential market for the downstream supply chain. The findings reveal a significant cost threshold for blockchain application and suggest that enterprises should dynamically adjust investment strategies based on a dual-dimensional "cost-preference" framework—for instance, prioritizing deployment for high-value-added products or sharing costs through consortium chains for SMEs. This research provides a theoretical framework for coordination mechanisms and empirical evidence for government subsidy policies and corporate investment optimization.

Keywords: Blockchain technology; Food supply chain; Cross-chain traceability; Coordination mechanism; Stackelberg game.

1. Introduction

Food quality and safety issues are fundamentally rooted in information asymmetry across the supply chain. Xie Kang et al. (2017) found that the regulatory dilemma in food safety stems from government oversight distorting consumer signals, preventing consumers from distinguishing quality through market prices [1]. Although blockchain technology offers a decentralized solution to enhance transparency, its implementation in multi-chain ecosystems—such as the "Internet + Catering" sector—is often hindered by high integration costs and fragmented coordination mechanisms.

Jiajia J et al. (2022) proposed a decentralized cross-chain data integrity verification scheme (DCIV) from the perspective of chain governance [2]. He Jing et al. (2014) first proposed the Food Supply-Demand Network (FSDN) concept, which represents a cross-chain, multi-functional, and multi-domain collaboration among enterprises across different supply chains in production, technology, management, logistics, and sales. This structure, characterized by its multilateral relationships, remains stable as long as supply and demand exist, outperforming the linear structure of traditional supply chains in stability [3].

However, the economic equilibrium and decision-making boundaries for collaborative investment remain under-explored. This study fills this gap by constructing a Stackelberg game model to analyze the interaction between upstream raw material (pork) and downstream processing (dumpling) supply chains. By quantifying the "cost threshold effect" and proposing a "Technology Investment Decision Matrix," we delineate the optimal conditions for blockchain adoption. Our findings provide a theoretical basis for profit distribution and offer strategic guidance for government subsidies and corporate technology deployment in heterogeneous supply chain environments.

2. Analysis of the Cross-Chain Traceability Coordination Mechanism

2.1. Model Construction

(1) Front-end Supply Chain (Pork Supply Chain)

The pork supply chain encompasses the entire trajectory from raw material procurement to terminal consumption. Upstream entities include raw material suppliers responsible for feed supply, production, and processing to ensure quality and safety, alongside feed distributors serving farming households. These entities constitute the upstream inception of the industry chain, spanning from livestock breeding to market-ready maturity and subsequent slaughtering. Slaughterhouses and downstream processing enterprises facilitate the conversion of livestock into market-available pork products.

(2) Back-end Supply Chain (Frozen Dumpling Supply Chain)

Similarly, the dumpling supply chain covers the full process from raw material acquisition to final retail. Procurement agents are responsible for sourcing compliant pork from the pork supply chain, which serves as the primary input for dumpling processing plants to produce frozen dumplings. Subsequently, distributors allocate the finished products to various retail points, where retailers facilitate the final sale to consumers.

(3) Blockchain Technology

Blockchain technology is fundamentally restructuring the collaborative relationships among all stakeholders within logistics and supply chain systems. In this framework, the blockchain platform functions as an information bridge between the two distinct supply chains. Leveraging cross-chain protocols, critical data from the pork supply chain (e.g., origin, quality inspection results) are recorded and shared with the dumpling supply chain. Concurrently, essential information from the dumpling supply chain (e.g., procurement data, processing parameters, and sales metrics) is shared back with the pork supply chain, achieving bidirectional information transparency. The cross-chain protocol serves as the architectural core of the blockchain platform, enabling data interoperability and sharing between these two previously independent supply chains within a unified network structure. Smart contracts facilitate the autonomous execution of contractual terms—such as quality benchmarks and transactional conditions—ensuring adherence to predefined standards and enhancing systemic transparency and automation. Furthermore, cryptographic techniques ensure data security during transmission, while permissioned access protocols balance data transparency with robust traceability.

2.2. System Architecture

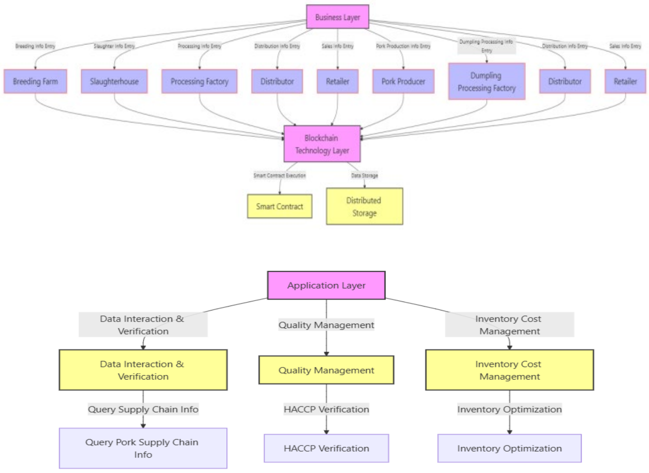

Figure 1. Architectural Diagram of the Blockchain-Based Food Supply Chain Cross-Chain Traceability System

(1) Business Layer

The Pork Supply Chain: This segment comprises several critical stages, including breeding farms, slaughterhouses, processing plants, distributors, and retailers.

Breeding Farms: Responsible for porcine husbandry, encompassing activities such as feed administration and health surveillance.

Slaughterhouses: Facilitate the slaughtering process once the livestock reaches market maturity.

Processing Plants: Execute post-slaughter processing, including carcass partitioning and primary packaging.

Distributors: Manage the logistics and allocation of processed pork products to retailers or direct consumers.

Retailers: Facilitate the final transaction of pork products to the end-consumer.

The Dumpling Supply Chain: This segment involves procurement agents, dumpling processing plants, distributors, and retailers.

Pork Producers: Function as the primary raw material suppliers for the dumpling supply chain.

Dumpling Processing Plants: Utilize pork as a fundamental ingredient to manufacture frozen dumpling products.

Distributors: Distribute frozen dumplings to retail outlets or directly to the consumer market.

Retailers: Execute the final sale of frozen dumplings to end-users.

(2) Blockchain Technology Layer

Smart Contracts: These facilitate the autonomous execution of contractual obligations, such as inventory timestamping, environmental monitoring, transaction recording, and the triggering of early-warning mechanisms. As a pivotal component of the blockchain traceability system, the smart contract module governs permission management and data access. It ensures that only requests satisfying predefined criteria are executed, thereby safeguarding the integrity and immutability of the blockchain network.

Distributed Storage: This serves as a decentralized repository for comprehensive data generated across the supply chain, including production, processing, and logistics information.

(3) Application Layer

The application layer serves as the user interface, providing essential functions and services that bridge the business and technology layers.

Product Quality Management: Stakeholders can monitor product quality in real-time to ensure compliance with Hazard Analysis and Critical Control Point (HACCP) standards. HACCP verification guarantees that every phase of the food production process adheres to rigorous safety protocols.

Inventory Cost Management: By leveraging blockchain technology, enterprises can achieve more precise market demand forecasting and optimize inventory management. This mitigates the risks of surplus or stockouts, thereby reducing overall storage costs.

Traceability Information Query: Consumers and regulatory authorities can access end-to-end information within the pork supply chain—spanning breeding, slaughtering, processing, and distribution. Similarly, relevant data regarding the dumpling supply chain, including raw material procurement, processing, and retail metrics, remain transparently accessible.

3. Analysis of the Coordination Mechanism for Blockchain-Based Cross-Chain Traceability

3.1. Construction of the Coordination Mechanism Model

3.1.1. Probem Description

This chapter constructs a supply chain network consisting of two entities: Supply Chain 1 (SC1), centered around a food manufacturer, and Supply Chain 2 (SC2), centered around a food distributor. Specifically, SC1 represents the "Pork Supply Chain" with a pork manufacturer as the core enterprise, while SC2 represents the "Frozen Dumpling Supply Chain" with a frozen dumpling distributor as the core enterprise. For analytical brevity, these are henceforth referred to as SC1 and SC2. In this framework, SC1 acts as the dominant market leader, while SC2 functions as the follower. Although both are independent supply chains, they maintain a progressive upstream-downstream relationship within the broader food industry value chain.

We posit that blockchain technology influences the profits of both supply chains through two primary mechanisms, thereby facilitating cross-chain coordination:

Upstream Cost Reduction: SC2 shares real-time market volatility data with SC1, effectively mitigating costs associated with inventory holding and stockouts.

Downstream Market Expansion: SC2 achieves enhanced quality management and communicates SC1's upstream traceability information to end-consumers, thereby stimulating consumer demand.

As a dominant entity in the food industry, SC1 possesses a massive market volume and supplies premium pork to multiple downstream chains, including those for frozen dumplings and burgers. The operational scope of SC1 spans from the selection of breeding stock and feed administration to vaccination, veterinary drug management, and slaughtering—encompassing the full-process quality supervision of pork from origin to processing. However, demand information from the consumer terminal is often distorted by the "bullwhip effect," leading to increased costs from routine inventory accumulation and unexpected market fluctuations.

Conversely, the operations of SC2 involve raw material procurement (e.g.,pork), processing, and demand management. Historically, SC2 has faced limitations in managing pork quality at the source, relying solely on quality inspections during procurement. If SC2 can achieve "source-to-end" traceability by accessing SC1's upstream data while sharing its own downstream market data back to SC1, both chains can secure a more integrated information chain. The following model explores the coordination principles of blockchain-enabled information sharing between these cross-chain entities.

3.1.2. Fundamental Assumptions

Assumption 1: SC1 and SC2 are independent entities—each comprising a full chain of wholesalers and retailers—with the potential for win-win cooperation. SC1 holds a monopoly position in the food market, supplying primary food sources to multiple downstream chains (e.g., dumplings and burgers). Consequently, this model assumes a Stackelberg game structure where SC2 makes decisions contingent upon the strategic choices made by SC1.

Assumption 2: SC1 and SC2 collaboratively adopt blockchain technology to facilitate active information sharing. This process incurs additional costs, including fixed technology investment and variable maintenance/operational costs. To simplify the calculations, let C_r denote the total marginal cost of blockchain technology. SC1 decides its basic control level over the technology γ_1, assuming a baseline of 50%), while SC2 shares the remaining cost burden.

Assumption 3: In practice, the food types and volumes required by SC1 and SC2 may vary. However, for computational simplicity, we assume a 1:1 ratio between frozen dumpling demand and pork material requirements in SC2's Material Requirements Planning (MRP). Let s represent the potential market size for pork in the food supply chain, β denote the consumer price sensitivity coefficient, and β represent the consumer preference coefficient for traceability information. The level of food traceability information primarily affects consumer utility and, consequently, product demand. A higher level of shared traceability information bolsters consumer trust and purchase intent, thereby expanding channel demand. Simultaneously, price impacts consumer utility. By accessing transparent circulation data provided by on-chain enterprises, consumers develop a positive preference effect, yielding additional revenue for the firms.

3.1.3. Parameter Settings

In this section, we construct an information coordination model for the food supply chain cross-chain traceability system based on Stackelberg game theory. The relevant parameters and notations are defined as follows:

Table 1. Parameters of the Information Coordination Model for Food Supply Chain Cross-Chain Traceability System

Variables	Definitions
π_1	Total profit of Food Supply Chain 1
π_2	Total profit of Food Supply Chain 2
${\pi_1}^*$	Total profit of Food Supply Chain 1 after Application of Blockchain
C_1	Selling price of pork in Supply Chain 1
P_2	Selling price of food products in Supply Chain 2
s	Potential market size of food (pork)
θ	Consumer price sensitivity coefficient
α	Attenuation coefficient of potential market due to lack of traceability information
β	Consumer preference coefficient for pork traceability information
γ_1	Blockchain technology cost for Supply Chain 1
γ_2	Blockchain technology cost for Supply Chain 2
γ_3	Blockchain technology cost for Supply Chain 1and Supply Chain 2
c	Total cost of blockchain technology implementation in the supply chain
C_H	Marginal cost of Supply Chain 1
${C_H}^*$	The Marginal Cost of Supply Chain 1 after Application of Blockchain

3.2. Analysis of the Coordination Mechanism

Based on the aforementioned fundamental assumptions, enterprises within the supply chain must formulate strategies to maximize their respective profits while considering their individual interests. The decision variables include the cost-sharing coefficients for the blockchain traceability system and the determination of product selling prices.

Stage I: Supply Chain 1 (SC1) determines the product price.

Stage II: Supply Chain 2 (SC2) determines the product price.

Consumer Demand Function for the Supply Chain:

$$D = s(1-\alpha) - \theta P_2 + \beta C_r$$

Profit Functions Prior to Blockchain Implementation: The profit functions for SC1 and SC2 are defined as follows:

$$\pi_1(C_1) = [s(1-\alpha\beta) - \theta P_2](C_1 - C_H)$$

$$\pi_2(C_2) = [s(1-\alpha\beta) - \theta P_2](P_2 - C_1)$$

Profit Functions Post-Blockchain Implementation: The profit functions for SC1 and SC2 are defined as follows:

$$\pi_1(C_1) = [s - \theta P_2 + \beta c](C_1 - C_H - c)$$

$$\pi_2(C_2) = [s - \theta P_2 + \beta c](P_2 - C_1)$$

Upon the implementation of blockchain technology, the attenuation factor (representing the negative impact of traceability information gaps on the potential market) becomes zero. Consequently, the potential market size of the food product is no longer subject to shrinkage.

3.2.1. Equilibrium Solution of the Stackelberg Game without Blockchain Implementation

The equilibrium derivation process without blockchain (utilizing the Backward Induction method) is as follows:

$$\pi_2(P_2) = [s(1-\alpha) - \theta P_2](P_2 - C_1)$$

First-order condition for P_2.

$$P_2 = \frac{s(1-\alpha)}{2\theta} + \frac{C_1}{2}$$

$$\pi_1(C_1) = [s(1-\alpha) - \theta P_2](C_1 - C_H)$$

First-order condition for C_1.

$$C_1 = \frac{s(1-\alpha)}{2\theta} + \frac{C_H}{2} = \frac{2s(1-\alpha) + 2\theta C_H}{4\theta}$$

Substituting the result of Stage 2 into Stage 1, the equilibrium prices are determined:

$$P_2 = \frac{3s(1-\alpha) + \theta C_H}{4\theta}$$

Substituting the equilibrium prices back into the respective profit functions results in:

$$\pi_1(C_1) = \frac{[s(1-\alpha) + \theta C_H]^2}{8\theta}$$

$$\pi_2(P_2) = \frac{[s(1-\alpha) + \theta C_H]^2}{16\theta}$$

The derivation above establishes the equilibrium solution for the Stackelberg game between the supply chains in the absence of blockchain technology, where neither SC1 nor SC2 has an incentive to deviate from their current strategies. Due to its dominant market position, SC1's profit is twice that of SC2.

Note: For the subsequent analysis and computational convenience, it is assumed that s (the potential market size of the supply chain food products) is sufficiently large.

3.2.2. Blockchain Coordination Mechanism

Proposition 1: The marginal cost of Supply Chain 1 (SC1) exerts a negative impact on the profits of all network members.

From the perspective of SC1's marginal cost, we detail the first blockchain-enabled cross-chain coordination mechanism: As a core link within a complex ecosystem, SC1's cost structure profoundly influences the profitability of the entire network. Marginal cost is particularly critical as it directly dictates the financial health of heterogeneous supply chains. Consequently, we propose a decentralized food quality traceability system leveraging blockchain. The system is designed to address quality control challenges in food production and distribution, utilizing smart contracts to ensure information transparency and veracity.

By utilizing blockchain, "source-to-end" management of food quality is achieved, facilitating the tracking of problematic products and real-time monitoring of quality status throughout the chain. Simultaneously, the system captures real-time market data and transmits it accurately to upstream SC1 members. This integration effectively mitigates the bullwhip effect—the distortion and amplification of demand signals caused by information latency. As a result, inventory management efficiency is enhanced and stockout risks are significantly reduced, thereby conserving vital resources, including time and capital, for all stakeholders.

Proposition 2: The attenuation factor—representing the negative impact of traceability information gaps on the potential market—negatively affects the profits of all members.

From the perspective of traceability information, we detail the second blockchain-enabled coordination mechanism: In contemporary society, increasing health consciousness has intensified consumer focus on food origins, natural growth processes, and chemical-free production. However, when consumers lack sufficient trust in food quality, the positive momentum of market demand is stifled. This mistrust permeates the market structure: first, it depresses selling prices, as consumers perceive quality signals as forgeable and gravitate toward lower-priced alternatives. Second, it alters demand dynamics, causing potential consumers—who would otherwise pay a premium for verified information—to seek alternative solutions.

Against this backdrop, the leader in the supply chain network must re-evaluate pricing strategies. To maintain competitiveness, suppliers may be compelled to lower wholesale costs or further reduce prices to sustain volume. Similarly, followers face pressure to adjust sales strategies to remain profitable despite declining price points. For the supply chain, this necessitates a delicate balance between profit margins and market demand.

By constructing the pre-blockchain Stackelberg model, this analysis demonstrates that blockchain adoption significantly enhances economic performance through two key coordination mechanisms. These mechanisms facilitate information alignment between chains, thereby reducing costs, expanding profit margins, and ultimately achieving cross-chain coordination.

In summary, blockchain technology catalyzes a revolutionary shift in cross-chain management by simultaneously reducing operational costs and expanding market potential. This not only yields direct economic benefits for individual firms but also propels the entire industry toward a more efficient, transparent, and sustainable trajectory.

3.2.3. Equilibrium Solution of the Stackelberg Game Post-Blockchain Implementation

The equilibrium derivation process after implementing blockchain (utilizing the Backward Induction method) is as follows:

$$\pi_2(P_2) = [s - \theta P_2 + \beta(y_1 + y_2)](P_2 - C_1 - y_2)$$

First-order condition for P_2:

By differentiating the profit function with respect to P_2, we obtain the optimal response function of SC2 relative to SC1:

$$P_2 = \frac{s}{2\theta} + \frac{C_1}{2}$$

First-order condition for P_1:

By substituting the response function into the profit function of SC1 and differentiating with respect to P_1

$$\text{SC1}: \pi_1(C_1) = [s - \theta P_2 + \beta(y_1 + y_2)](C_1 - C_H - y_1)$$

$$C_1 = \frac{1}{2\theta}[2s + \beta(y_1 + y_2)] + \frac{1}{2}(y_1 - y_2 + C_H)$$

the equilibrium prices are derived:

$$P_2 = \frac{s + \beta c}{2\theta} + \frac{c + C_H}{4}$$

By substituting the equilibrium prices back into the respective profit functions, we obtain:

$$\pi_1 = \frac{[s + \beta c - \theta(c + C_H)]^2}{8\theta}$$

$$\pi_2 = \frac{[s + \beta c - \theta(c + C_H)]^2}{16\theta}$$

The above derivation delineates the equilibrium solution of the Stackelberg game between the supply chains following the adoption of blockchain technology. Under these conditions, neither SC1 nor SC2 has an incentive to deviate from their strategies. Notably, SC1 maintains its dominant market position, with its profit being four times that of SC2, indicating a further consolidation of its competitive advantage compared to the pre-blockchain scenario.

Proposition 3: The relationship between the profits of SC1 and SC2 and the investment in blockchain technology is contingent upon the equivalence between the consumer price sensitivity coefficient θ and the traceability information preference coefficient β. Specifically, if $\theta = \beta$, the profit is independent of the blockchain technology cost. Conversely, if $\theta \neq \beta$, profit becomes correlated with technology investment. $s - \theta(y_3 + C_H) > 0$ and assuming all other parameters remain constant, if$\beta > \theta$, the profit increases monotonically with the total investment in blockchain technology.

Proposition 4: When $y_3 \neq \frac{\theta}{\theta-\beta}(C_H - C_H{}^*)$, when the total cost of blockchain implementation satisfies this condition, the application of blockchain technology facilitates value appreciation within the food supply chain.

Proof: Under standard market conditions, the information preference coefficient βtypically exceeds the price sensitivity coefficient θ.

Assuming a sufficiently large market size s
let

$$\pi_1{}^* - \pi_1 - = \frac{[s+\beta y_3-\theta(y_3+C_H)]^2}{8\theta} - \frac{(s+-\theta C_H)^2}{8\theta} \geq 0.$$

By expanding the squared terms, we derive that:

$$s - \theta C_H \leq s + \beta y_3 - \theta(y_3 + C_H{}^*)$$

$$y_3 \neq \frac{\theta}{\theta - \beta}(C_H - C_H{}^*)$$

The application of blockchain technology yields significant value appreciation for both food supply chains.

3.3. Conditions for Effective Coordination via Blockchain

Based on the preceding theoretical analysis, this study utilizes matlab software to conduct a comparative numerical analysis of the profits of both supply chains before and after the implementation of blockchain-based cross-chain traceability. This simulation aims to verify the theoretical model and further explore the specific conditions under which blockchain effectively coordinates heterogeneous supply chains. To ensure the generalizability of the results, the following parameter assumptions are established, drawing upon a comprehensive review of relevant empirical literature:

$$s = 20, \theta = 0.7, C_H = 20, \alpha = 0.3$$

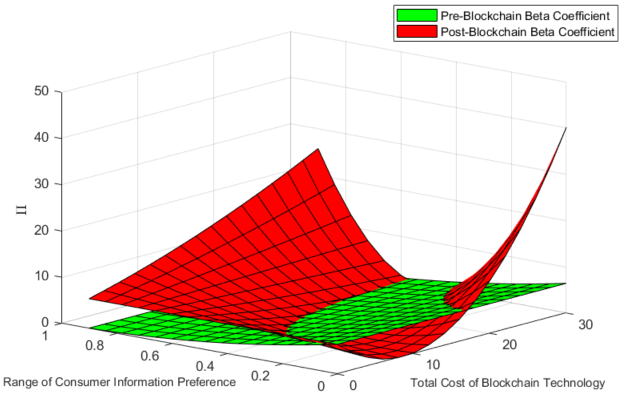

Figure 2. Three-dimensional Profit Diagram of Different Blockchain Costs and Pork Traceability Information Preference

The figure above illustrates the three-dimensional relationship between the profits of Supply Chain 1 (SC1), the consumer preference for pork traceability information, and the costs associated with blockchain technology, both prior to and following the implementation of the technology. The efficacy of blockchain in coordinating the food supply chain hinges critically on the specific combination of total blockchain investment and the intensity of consumer preference for traceability information. Consequently, this leads to the formulation of a "Cost-Preference" dual-dimensional dynamic investment strategy. To more precisely reflect the outcomes under specific parameter combinations, we calculated the profit differential for SC1 before and after blockchain adoption, generating Figure 4—a contour plot representing the equilibrium boundaries where profits remain equal.

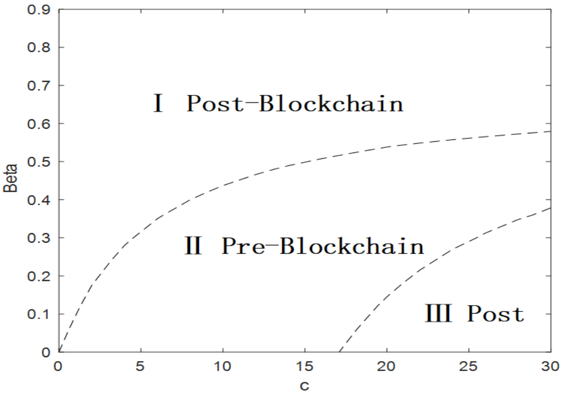

Figure 3. Decision Map for Blockchain Adoption under Different Parameter Combinations

By plotting the iso-profit contours (where profits before and after blockchain adoption are equal), we select a specific cross-sectional profile of profit under varying blockchain costs and consumer preferences for pork traceability information. This allows for a deeper investigation into the decision boundaries for blockchain application across different parameter combinations. Regions I, II, and III represent strategic recommendations for blockchain adoption under various combinations of technology costs and market preferences.

Specifically, blockchain application is recommended in Regions I and III. When mapped back to the three-dimensional profit surface in Figure 2, these regions correspond to the areas where the post-blockchain profit surface lies above the pre-blockchain surface, indicating that blockchain implementation yields a profit surplus (value appreciation). Conversely, under the parameter combinations in Region II, the post-blockchain profit is lower. This suggests that when consumer preference for traceability information is weak, blockchain technology lacks a competitive advantage unless the investment costs are further optimized. Furthermore, Figure 2 intuitively demonstrates that the profits achieved under the parameter combinations in Region III significantly exceed those in the more conservative Region I.

3.4. Sensitivity Analysis of Key Factors

3.4.1. Total Cost of Blockchain Technology Implementation

Let the set of total implementation costs:
$c = \{0, 6, 12, 18, 24\}$.

As the total cost of blockchain technology increases, the evolution of profit relative to the consumer preference coefficient for pork traceability information β is illustrated in Figure 4.

The figure illustrates the profit trends of Supply Chain 1 (SC1) as a function of the consumer preference coefficient for pork traceability information across various blockchain cost levels. The cost levels range from low to high: $c = \{0, 6, 12, 18, 24\}$.The horizontal axis represents the consumer preference coefficient, where a higher value indicates that consumers place greater importance on traceability information. The vertical axis represents profit.

At lower blockchain cost levels, profit increases marginally and linearly with the preference coefficient, exhibiting a flatter curve with minimal convexity. As the cost level increases, the convexity of the curves becomes more pronounced. At higher blockchain cost levels, profit initially declines rapidly at low preference values but begins to rise sharply once β approaches 0.7, forming a distinct U-shaped curve. This indicates that at high cost levels, returns are highly sensitive to variations in β. The entry cost of blockchain significantly influences the strategic choices of food enterprises; excessive entry costs may inhibit the enthusiasm for data on-chaining, thereby hindering the promotion of blockchain technology in food traceability systems.

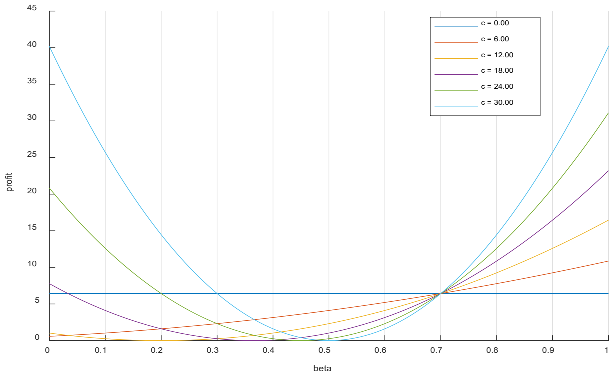

Figure 4. Trends in Profit relative to Information Preference Coefficients under Different Blockchain Costs

For all cost levels ($C \neq 0$), there exists a critical threshold for the preference coefficient (approximately at $\beta = 0.7$). Prior to this threshold, the model exhibits high robustness, meaning profit is insensitive to parameter fluctuations, and the quality of decisions remains stable despite uncertainty in information preference. Beyond this point, profit begins to increase significantly [4].

These findings offer two critical strategic insights for enterprises:

Prior to committing to high fixed costs for blockchain technology, enterprises must conduct thorough consumer behavior research to precisely determine the markets preference coefficient for traceability information.

Since each curve initiates at a specific value when $\beta = 0$, this point can be defined as the baseline profit. The enterprise's objective is to leverage blockchain to surpass this baseline. Given a fixed cost investment, firms can employ marketing instruments—such as food safety educational videos, advertorials, and creative advertising—to enhance consumer perceptions and shift the preference coefficient toward the value-appreciation zone, thereby increasing the willingness to pay for verified information. For instance, taking $C = 18$ as an example, by drawing a line parallel to the horizontal axis through the y-intercept, the intersection with the curve marks the threshold where profit enters the value-appreciation zone.

Notably, when the preference coefficient $\beta = 0.7$, the curves for all cost levels intersect at a single point, indicating that at this specific threshold, profit becomes independent of blockchain implementation costs.

3.4.2. Consumer Preference Coefficient for Pork Traceability Information

Among the four attributes of information—origin, certification, traceability, and accreditation—consumers exhibit a higher preference for traceability (excluding accreditation), with a willingness to pay a premium of over 20% for information traceable back to the breeding stage. However, in actual production, the adoption rate of traceability information among farmers remains below 10% [5]. Based on this, we designate the consumer preference coefficient for traceability β as a critical exogenous variable to explore its impact on supply chain profit and blockchain costs.

Assuming consumer sensitivity (or preference) toward product traceability information follows a uniform distribution $\beta \sim U[0,1]$[6], we discretize the values as $\beta = \{0.1; 0.2; 0.5; 0.7; 0.9\}$to represent varying degrees of market preference. The impact of increasing β on profit relative to the total cost of blockchain technology is shown in Figure 5.

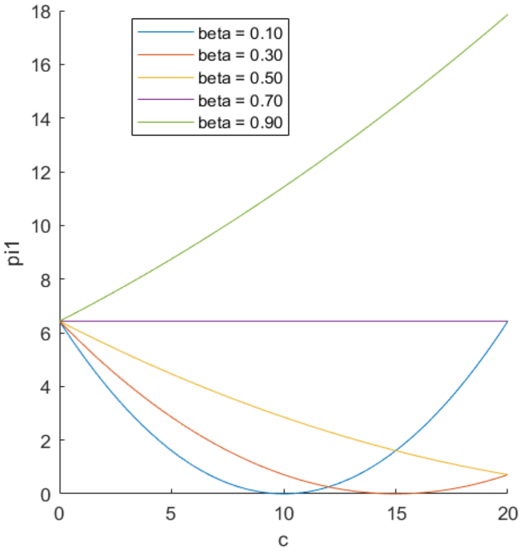

Figure 5. Trends in Profit relative to Blockchain Costs under Different Information Preference Coefficients

The figure above depicts the variation in SC1s profit as a function of blockchain technology costs across different preference levels $\beta = \{0.1; 0.2; 0.5; 0.7; 0.9\}$. The horizontal axis represents the total cost investment. We categorize the discussion based on the specific value of β, which can guide both one-time investment decisions and continuous investment strategies.

At an extremely low preference level $\beta = 0.1$), the curve is a symmetric convex shape, with profit reaching its minimum at $C = 10$. Since the curve is symmetric around $C = 10$, this implies that when preference is minimal, lower costs yield higher profits. While profit increases slightly between $C = 10$ and C =20, the marginal profit per unit of cost is nearly zero, resulting in significant sunk costs. In such cases, firms should reallocate capital to other value-adding activities to enhance overall risk resistance. At lower preference levels $\beta = 0.2/0.5$, the curves show a downward trend, suggesting that blockchain adoption is not economically viable. This conclusion can be generalized to the interval$0 < \beta < \theta$. (θ is the price sensitivity coefficient). At the specific threshold where $\beta = 0.7$(i.e., $\beta = \theta$), the curve is horizontal and inelastic, meaning profit remains constant regardless of cost. At a very high preference level ($\beta = 0.9$), the curve trends upward, encouraging continuous investment in blockchain technology. This conclusion can be generalized to $1 > \beta > \theta$

In this model, the consumer price sensitivity coefficient is set to 0.7; thus, 0.7 serves as the critical value that determines the positive trend of profit relative to blockchain costs. In practice, enterprises seeking profit growth through blockchain must assess the actual market price sensitivity. When $\beta < \theta$, marketing efforts are required in the early stages of the project lifecycle to enhance consumer awareness. When $\beta \geq \theta$, the marginal profit rate per unit of cost can be calculated through the model to support continuous blockchain investment decision-making.

4. Conclusion

This research addresses the critical challenges of high information barriers and low collaborative efficiency in food supply chain cross-chain traceability by innovatively introducing a blockchain-based coordination mechanism. Through the construction of a Stackelberg game model involving pork and frozen dumpling supply chains, we systematically reveal the mechanism by which blockchain enhances systemic performance by mitigating information asymmetry, optimizing cost structures, and stimulating market demand. Our findings demonstrate a significant "cost threshold effect" in blockchain adoption: once investment surpasses the critical threshold, supply chain profits can reach up to twice those of the traditional model, validating the economic feasibility of blockchain in cross-chain collaboration.

Theoretical and Practical Contributions:

Theoretical Expansion: This study extends the boundaries of supply chain coordination theory by quantifying blockchain technical features as key variables within a game-theoretic framework.

In consumer markets with rapid information dissemination and high information sensitivity, there is a greater willingness to pay for highly traceable food products, which also facilitates the governments pilot program implementation during the initial phase of supply chain traceability system construction. [7] Empirical Insights: Numerical simulations and sensitivity analyses conducted via MATLAB reveal a dynamic alignment between consumer preference and technical investment. Specifically, when $\beta \geq 0.7$, each unit of blockchain investment yields a 2.2% profit increase. Conversely, when $\beta < 0.7$, technical costs must be strictly contained within 18 units to ensure positive returns.

Limitations and Future Research:

Despite these contributions, this study is subject to several limitations:

the assumption of perfectly rational decision-making neglects irrational factors such as risk aversion;

the focus remains on dual-chain synergy, overlooking the complexities of heterogeneous multi-chain networks;

the reliance on static simulations lacks real-time validation in volatile markets.

Future research should focus on:

Integrating Behavioral Economics to analyze the impact of finite rationality and risk preferences on collaborative strategies.

Expanding to Multi-chain Scenarios to design cross-chain consensus mechanisms that resolve interoperability challenges between heterogeneous chains.

Leveraging IoT and Digital Twins to upgrade from "ex-post traceability" to "real-time monitoring," achieving seamless mapping between physical and digital supply chain assets. [8]

Conducting Multi-case Empirical Studies to verify the generalizability of blockchain across various firm scales and food categories.

Our findings provide a strategic decision map for stakeholders. Large-scale enterprises should prioritize blockchain deployment for high-value-added products (e.g., organic food) to leverage high consumer preference for rapid ROI. Small and medium-sized enterprises (SMEs) can mitigate financial barriers through consortium chain models. Furthermore, regulatory bodies can utilize the "cost threshold" theory to design differentiated subsidy policies, accelerating the industrys digital transformation. As technologies such as AI and Edge Computing converge with blockchain, the food supply chain will evolve from "linear coordination" toward "intelligent network synergy," ensuring a secure and sustainable food ecosystem.

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