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Research on the Mechanism for Building a Supply Chain Ecosystem in Hainan Free Trade Port under the Digital Economy

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Abstract This study explores the construction mechanism of the supply chain ecosystem in the Hainan Free Trade Port against the backdrop of the digital economy. By designing a supply chain traceability model and combining differential privacy algorithms with blockchain technology, a solution that balances data privacy protection and sharing efficiency is proposed. The economic effects of closed-loop supply chain strategies under different platform models are analyzed, and based on the geographical and policy advantages of the Hainan Free Trade Port, a path for its integration into the global supply chain network is proposed. Through an analysis of the supply chain impact in the Hainan Free Trade Port, it is found that when the construction cost of blockchain is sufficiently small ($F \to 0$), there are two thresholds, $0 < \underline{\alpha_1} < \overline{\alpha_1} < 1$, such that $\underline{\alpha_1} < \alpha < \overline{\alpha_1}$ then introducing blockchain technology can increase corporate profits, i.e., $\pi_B^* > \pi_N^*$; otherwise, introducing blockchain technology will reduce corporate profits, i.e., $\pi_B^* < \pi_N^*$ There exists a threshold $\tilde{F}_1$: 1) When $\alpha < \tilde{\alpha}_1$ and $F > \tilde{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_N^* > \pi_B^*$; 2) When $\alpha < \tilde{\alpha}_1$ and $F < \tilde{F}_1$, $\prod_N^* > \prod_B^*$ and $\pi_B^* > \pi_N^*$; 3) When $\alpha > \tilde{\alpha}_1$ and $F > \tilde{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_B^* > \pi_N^*$; 4) When $\alpha > \tilde{\alpha}_1$ and $F < \tilde{F}_1$, then $\prod_B^* > \prod_N^*$ and $\pi_B^* > \pi_N^*$.

Index Terms Hainan Free Trade Port, supply chain, differential privacy algorithm, blockchain technology.

I. Introduction

Currently, China's economic reform has entered a critical phase characterized by deep-seated challenges and intense competition. In the face of an ever-changing international competitive landscape, to enhance China's competitive edge in global economic and trade activities, its institutional mechanisms and systems must become more open, integrated, inclusive, and innovative [1]-[3]. The construction of the Hainan Free Trade Port is a major initiative by China to promote reform through opening up and build a new open-type economic system. The state supports Hainan in pursuing comprehensive reform and innovation, actively promoting the free and convenient flow of goods and production factors, and using high-level opening up to advance social reform comprehensively [4]-[6]. In establishing the Hainan Free Trade Port, by learning from and drawing on the mature experiences of foreign free trade ports—such as management methods, operational models, and institutional arrangements—and aligning with global high-standard economic rules, China aims to gradually form a new open-type economic system. This will further enhance its economic leadership role for other regions in China and explore new pathways and accumulate new experiences for higher-level reform and opening-up [7]-[10]. A free trade port is a special economic functional zone with the highest level of openness globally. It is typically established within the territory of a country or region, outside customs control checkpoints [11], [12]. One of its functions is to allow the free entry and exit of goods and capital from abroad, with all or most goods entering or exiting the port exempt from tariffs; The second function is to permit business activities such as the free storage, exhibition, disassembly, modification, repackaging, sorting, processing, and manufacturing of goods within the free trade port [13]-[15].

In the current era of global digitalization, China is actively promoting the development of the digital economy to achieve economic transformation and upgrading and high-quality growth. As a new economic model, the digital economy, with its strong innovative driving force and efficient resource allocation capabilities, is reshaping the global economic landscape [16], [17]. China's digital economy has achieved remarkable accomplishments in recent years, with rapid development in areas such as e-commerce, mobile payments, digital finance, and smart manufacturing, bringing significant benefits to economic growth and social progress [18], [19]. Against this backdrop, the Hainan Free Trade Port implements a special tax system featuring “zero tariffs, low tax rates, and a simplified tax regime,” providing digital enterprises with a more lenient tax environment [20], [21]. Additionally, the Hainan Free Trade Port's innovative policies in areas such as trade and investment liberalization and facilitation, as well as cross-border capital flow liberalization and facilitation, have created favorable conditions for cross-border cooperation and international exchange in the digital economy [22], [23]. Furthermore, in the free trade port, high-quality industries have been aggregated and disseminated, enabling the effective integration of supply chains. This has facilitated the gradual advancement of industries that were previously at the lower end of the value chain toward higher-end levels, thereby optimizing China's industrial structure [24]. Therefore, it is necessary to establish a supply chain ecosystem tailored to the Hainan Free Trade Port to support its sustainability.

The establishment of the free trade port has provided a free and convenient platform for trade development, actively creating an internationalized operational environment, and continuously providing favorable conditions for supply chain development, breaking through development constraints faced by enterprises in areas such as administrative management, trade rules, regulatory systems, and the financial sector [25], [26]. Today, Hainan Free Trade Port, due to its unique geographical location, has become a key node in the supply chains of numerous enterprises. Literature [27] summarizes that under a series of policy measures, such as zero tariffs and high-quality transportation services, the logistics industry in the Hainan Free Trade Port is poised to become China's most open free trade port. Its logistics services have developed rapidly since 2021 and are expected to become an important logistics hub for China's trade with other countries.

In the context of the digital economy, Literature [28] suggests that the construction of the Hainan Free Trade Port's global supply chain relies on blockchain technology to establish a platform for sharing supply chain information, thereby achieving information compensation services. To this end, an information compensation model was created. Meanwhile, Literature [29] utilized the Fabric blockchain to construct a port supply chain system, which includes features such as smart contracts, access control mechanisms, enterprise lists or order queries, and cargo order uploads, thereby enhancing supply chain operational efficiency. Literature [30] explores the dynamics of price and profit in the free trade port supply chain from a blockchain-based consumer sensitivity perspective, finding that blockchain-supported supply chains have significant profit advantages and are less affected by other factors.

Additionally, literature [31] designs a dual-channel supply chain network scenario in a complex system context to investigate the impact of blockchain platform selection issues in the free trade port on pricing and redesign decisions within manufacturers' supply chain networks, providing reference for enterprise supply chains. Literature [32] provides an algorithm that runs in polynomial time for supply chain planning in free trade zones and under uncertain demand conditions, and introduces u-regret robust optimization for uncertain demand. Literature [33] points out that in a free trade environment, hub ports utilize global supply chains, and under advanced institutional policies, the creation of international trade facilitation centers to centralize cross-border customs procedures is a mature trend for ports.

This paper first proposes a data perturbation mechanism based on differential privacy, utilizing the Laplace algorithm, binary random responses, and an exponential mechanism to achieve privacy protection. A smart contract layer is designed to enable automated noise addition and hierarchical data storage. A comparative analysis is conducted to examine the impact of blockchain technology on the demand, pricing, and profits of green products under resale and agency models, revealing the sensitivity patterns of blockchain costs and commission rates. Combining the geographical advantages of the Hainan Free Trade Port, this paper proposes a differentiated path for it to connect with the ASEAN industrial chain. Through impact analysis, it verifies the differentiated effects of blockchain on corporate profits and the willingness of entities to participate. It extracts key influencing factors and explores the driving role of government policies and product value in supply chain evolution.

II. Mechanism for Building a Supply Chain Ecosystem in Hainan Free Trade Port

Against the backdrop of the accelerated development of the global digital economy and the deepening of regional economic integration, the intelligent and secure transformation of supply chain ecosystems has become a key issue in the construction of free trade ports. This study focuses on the Hainan Free Trade Port and systematically explores the mechanisms for constructing its supply chain ecosystem.

II. A. Supply Chain Traceability Model Design

II. A. 1) Disturbance Mechanism

This section focuses on the design of differential privacy algorithms for data sharing in supply chain traceability scenarios and implements differential privacy mechanisms at the smart contract layer. Before supply chain entities (such as manufacturers and distributors) upload product information to the blockchain network for data sharing, the differential privacy algorithm embedded within the smart contract automatically applies noise perturbation to the data, thereby obscuring critical data information. This ensures that even if the data is publicly available, it is difficult to infer specific product information through differential attacks. The following details the algorithm's implementation.

First, since supply chain data is diverse in type, to ensure blockchain operational efficiency, we only apply noise processing to sensitive data. For unstructured sensitive data, we classify it into numerical and non-numerical data types.

For numerical data such as product dimensions, transaction volume, transaction price, etc., we use the mainstream Laplace algorithm. The core of the Laplace noise function is to add a random number that conforms to the Laplace distribution to the numerical data. The generating function of this noise b can be calculated by inverting the Laplace cumulative distribution function (CDF), and its expression is as follows:

$$b = \mu - \beta \cdot \operatorname{sgn}(\alpha - 0.5) \cdot \ln(1 - 2|\alpha - 0.5|) \ \alpha \sim UNI(0,1) \tag{1}$$

where μ is an unknown parameter of the Laplace distribution, typically set to 0 so that the noise is centered at 0. β is the scale function of the Laplace distribution, which is related to the privacy budget ϵ of differential privacy, specifically $\beta = \Delta f / \epsilon$, where Δf is the sensitivity of the query function. $sgn(\cdot)$ is the sign function, which adjusts the sign of the noise based on the value.

By adding the noise b to the original data, we obtain the final numerical formula $f_M(D)$ that satisfies ϵ-differential privacy:

$$f_M(D) = f(D) + Lap\left(\frac{\Delta f}{\epsilon}\right) \tag{2}$$

This involves adding Laplace noise to the results of the original query data $f(D)$ to achieve ϵ-differential privacy. $Lap\left(\frac{\Delta f}{\epsilon}\right)$ represents the noise term that conforms to the Laplace distribution, whose scale parameter is determined by the sensitivity Δf at the time of the query and the privacy budget ϵ. It can be seen that the privacy budget is inversely proportional to the size of the added noise term. A lower privacy budget means more noise, thereby providing stronger privacy protection, but this sacrifices the practicality of the data, which is why the privacy budget becomes lower. An appropriate privacy budget needs to be carefully selected here to strike a balance between protecting validity and data practicality.

Non-numeric data, i.e., discrete data, is categorized into two types in this paper: binary and enumerated. Binary data includes examples such as product quality status, inventory status, and shipment confirmation. Since there are only two possible values, we employ the Binary Random Response (BRR) mechanism. For enumerated data, such as product status, shipping method, and temperature control requirements, we use an exponential mechanism to achieve data perturbation. The BRR mechanism enhances privacy protection by randomly altering Boolean values (true/false). Even if data is leaked, attackers would struggle to determine the true values of individual records. Additionally, due to its simple implementation mechanism, it is more computationally efficient compared to other methods. In the BRR mechanism, for any binary data item, the true value is retained with probability p and replaced with its opposite value with probability $q = 1 - p$. If a user's data domain has y and y', the probabilities are calculated using the following formula:

$$\Pr[M(y) = y'] = \begin{cases} \dfrac{e^{\epsilon}}{e^{\epsilon} + 1} & if\ y = y' \\ \dfrac{1}{e^{\epsilon} + 1} & if\ y \neq y' \end{cases} \tag{3}$$

After randomization through the BRR mechanism, even if the perturbed data is observed, the true values of the original data items cannot be determined.

The exponential mechanism is another common differential privacy mechanism. Unlike Laplace noise, which simply adds noise to the numerical output to achieve differential privacy, However, for non-numeric data, its output is an element from a set of discrete data $\{R_1, R_2 \ldots R_n\}$. The overall idea of the exponential mechanism is: when a query is received, instead of deterministically outputting an R_i structure, it first assigns a probability weight to each possible output. The probability weight is determined by a scoring function. The formula for the scoring function is as follows:

$$f : D^d \times Y \rightarrow R \tag{4}$$

Here, D^d denotes the domain of the dataset, and d is the dimension of the domain. Y is the set of all potential outputs. R denotes the set of real numbers. That is, the scoring function $f(x,y)$ accepts two inputs: the original dataset x and the potential output candidate y. The final output is a real number value that represents the suitability of the input candidate y for the given original dataset. Outputs with high scores have high probabilities, while those with low scores have low probabilities. If the sensitivity of the current query is Δf, the probability formula for the output candidate y is:

$$\Pr\left[M(d)=y\right]=\frac{\exp\left(\frac{\varepsilon}{2\Delta f}\cdot f(x,y)\right)}{\sum_{i=1}^{n}\exp\left(\frac{\varepsilon}{2\Delta f}\cdot f(x,y_i)\right)} \tag{5}$$

The probability of each candidate output y being selected is proportional to the exponential value of its scoring function $f(x,y)$, with the denominator being the sum of the scoring indices of all candidate outputs, which is used for normalization to ensure that the sum of all probabilities is 1. Through the exponential mechanism, output candidates with higher scoring functions have a higher probability of being selected, but at the same time, each candidate is guaranteed a certain chance of being selected, thereby protecting privacy.

II. A. 2) Smart Contract Layer Implementation

By integrating differential privacy mechanisms into blockchain smart contracts, user data is automatically processed by chaincode to obfuscate sensitive data during upload. Different types of data are processed using distinct random noise functions, with the original data stored in a private ledger to support traceability queries, while the noise-processed data is stored in a public ledger on the blockchain network for data analysis and other purposes.

The process is divided into three main steps:

(1) Chaincode deployment: Endorsing nodes are responsible for writing the chaincode function and configuring access permissions for organizational nodes. The chaincode is then pushed to the blockchain network by the node and broadcasted. To ensure network consistency, all participating nodes must update their local backups to synchronize with the latest network state.

(2) Data upload: Users request data upload via the chaincode function. After the chaincode function verifies the data format, it processes the data using the corresponding noise-adding algorithm.

(3) Data Query or Verification: When users need to perform traceability queries or verify the authenticity of their uploaded data, they first send a request to the backend. The backend first verifies whether the user has query permissions, then requests the sorting node to perform verification. The sorting node broadcasts the request to the endorsing nodes. After the endorsement node verifies the user's identity, it retrieves the data from the public ledger and combines it with the noise information in the private ledger for denoising processing, finally returning the traceability information to the user.

II. B.Closed-loop supply chain strategies under different platform models

II. B. 1) Use of blockchain technology for sales through resale models (RB)

In this scenario, manufacturers adopt blockchain technology and sell products through the platform's resale channels. Manufacturers use blockchain technology to disclose green product attributes and recycling information in real time, so consumers have complete confidence in the green credentials and recycling information of the products. Therefore, demand is characterized as follows:

$$D^{RB}=a-p+g \tag{6}$$

where a represents the potential market size. g represents the greenness of the product; the higher the value, the more environmentally friendly the product is. p represents the sales price. At this point, consumers fully trust green products, so $\alpha=1$ and $\beta=1$.

At the same time, manufacturers need to bear the cost of adopting blockchain technology, so the manufacturer's profit function is the sum of positive sales profits and recycling revenues minus the R&D costs of green products and the costs of applying blockchain technology:

$$\Pi_M^{RB}=\left(w+t\tau-c_b\right)D^{RB}-\mu g^2 \tag{7}$$

The platform's profit function is expressed as the sum of positive sales profits and recovery revenues minus recovery costs:

$$\Pi_i^{RB} = \left(p - w + b\tau\right) D^{RB} - kr^2 \tag{8}$$

Proposition 1 presents the equilibrium decisions of manufacturers and platforms under scenario RB, as well as the equilibrium profits of manufacturers.

Proposition 1: When $k > k_3$ and $\mu > \mu_3$, the equilibrium decisions of manufacturers and platforms under scenario RB, as well as the equilibrium profits of manufacturers, are as follows:

$$w_M^{RB*} = \frac{\mu(4k - b^2 - 2tb)a + c_b[\mu(4k - b^2) - k]}{2\mu(4k - b^2 - tb) - k} \tag{9}$$

$$g_M^{RB*} = \frac{k(a - c_b)}{2\mu(4k - b^2 - tb) - k} \tag{10}$$

$$p_i^{RB*} = \frac{2\mu a(3k - b^2 - tb) + kc_b(2\mu - 1)}{2\mu(4k - b^2 - tb) - k} \tag{11}$$

$$\tau_i^{RB*} = \frac{b\mu(a - c_b)}{2\mu(4k - b^2 - tb) - k} \tag{12}$$

$$\Pi_M^{RB*} = \frac{\mu k(a - c_b)^2}{2\mu(4k - b^2 - tb) - k} \tag{13}$$

Inference 1 provides a sensitivity analysis of the manufacturer's equilibrium decision and equilibrium profit with respect to parameters under scenario RB.

Inference 1: Under scenario RB, the sensitivity analysis of the manufacturer's equilibrium decision and equilibrium profit with respect to parameters is as follows:

(1) $\frac{\delta w_M^{RB*}}{\delta c_b} > 0$, $\frac{\delta p_M^{RB*}}{\delta c_b} > 0$

(2) $\frac{\delta g_M^{RB*}}{\delta c_b} < 0$

(3) $\frac{\delta \Pi_M^{RB*}}{\delta c_b} < 0$

As can be seen from Inference 1, both the manufacturer's wholesale price and sales price increase as blockchain costs increase. Meanwhile, the product's green rating decreases as blockchain costs increase, because as blockchain costs rise, manufacturers need to reduce green ratings to cut R&D costs in order to maintain profits. Additionally, manufacturers' profits also decrease as blockchain costs increase.

II. B. 2) Use of blockchain technology for sales through an agency model (AB)

In this scenario, manufacturers adopt blockchain technology and sell products through the platform's agency channels. Manufacturers use blockchain technology to disclose green product attributes and recycling information in real time, so consumers have complete confidence in the green credentials and recycling information of the products. Therefore, demand is characterized as follows:

$$D^{AB} = a - p + g \tag{14}$$

where a represents the potential market size. g represents the greenness of the product; the higher the value, the more environmentally friendly the product is. p represents the sales price. At this point, consumers fully trust green products, so $\alpha = 1$ and $\beta = 1$.

At the same time, manufacturers need to bear the cost of adopting blockchain technology, so the manufacturer's profit function is the sum of positive sales profits and recycling revenues minus the R&D costs of green products and the costs of applying blockchain technology:

$$\Pi_M^{AB} = [(1 - \phi)p - c_b + t\tau]D^{AB} - \mu g^2 \tag{15}$$

The platform's profit function is the sum of positive sales profits and recovery revenues minus recovery costs:

$$\Pi_i^{AB} = (\phi p + b\tau) D^{AB} - kr^2 \tag{16}$$

Proposition 2 gives the equilibrium decisions of manufacturers and platforms under scenario AB, as well as the equilibrium profits of manufacturers.

Proposition 2: When $k > k_4$ and $\mu > \mu_4$, the equilibrium sales price and greenness of manufacturers are:

$$p_M^{AB*} = \frac{2\mu[k(1-\phi) - tb]a + [2\mu - (1-\phi)]kc_b}{4\mu k(1-\phi) - 2tb\mu - (1-\phi)^2 k} \tag{17}$$

$$g_M^{AB*} = \frac{k(1-\phi)[(1-\phi)a - c_b]}{4\mu k(1-\phi) - 2tb\mu - (1-\phi)^2 k} \tag{18}$$

$$\tau_i^{AB*} = \frac{b\mu[(1-\phi)a - c_b]}{4\mu k(1-\phi) - 2tb\mu - (1-\phi)^2 k} \tag{19}$$

$$\Pi_M^{AB*} = \frac{\mu k[(1-\phi)a - c_b]^2}{4\mu k(1-\phi) - 2tb\mu - (1-\phi)^2 k} \tag{20}$$

Inference 2 provides a sensitivity analysis of the manufacturer's equilibrium decision and equilibrium profit with respect to parameters under scenario AB.

Inference 2: Under scenario AB, the sensitivity analysis of the manufacturer's equilibrium decision and equilibrium profit with respect to parameters is as follows:

(1) $\frac{\delta g_M^{AB*}}{\delta c_b} < 0$

(2) $\frac{\delta \Pi_M^{AB*}}{\delta c_b} < 0$

(3) $\frac{\delta g_M^{AB*}}{\delta \phi} < 0$, $\frac{\delta D_M^{AB*}}{\delta \phi} < 0$, $\frac{\delta \tau_M^{AB*}}{\delta \phi} < 0$

(4) When $c_b < 2a\mu$, $\phi < [0, \max(0, \phi_3)] \cup \phi > [\min(\phi_4, 1), 1]$ then $\frac{\delta p^{AB}}{\delta \phi} < 0$;

When $c_b > 2a\mu$, $\phi \in [\max(0, \phi_3), \min(\phi_4, 1)]$ under which $\frac{\delta p^{AB}}{\delta \phi} < 0$.

As shown in Corollary 2, the manufacturer's profit decreases as blockchain costs increase. The product's greenliness decreases as blockchain costs increase, because as blockchain costs rise, manufacturers must reduce greenliness to cut R&D costs in order to maintain profits. Additionally, after adopting blockchain technology, the equilibrium product greenness, demand, and recycling rate decrease as the commission rate increases. The equilibrium sales price still depends on the impact of blockchain costs when the commission rate changes. When blockchain costs are low, the equilibrium sales price first decreases and then increases as the commission rate increases.

II. C.Key Focus Areas for the Development of Hainan Free Trade Port

From a global perspective, the trend of the global manufacturing supply chain shifting to ASEAN is irreversible. For example, the global textile supply chain has already shifted significantly from China to Vietnam. As Chinese textile and apparel, footwear, and furniture companies increasingly choose to establish factories in Southeast Asia, this will trigger significant changes in cargo flow and direction. Currently, among the export products of Southeast Asian countries, excluding resource-based industries such as mineral fuels, the main export categories are footwear and accessories (footwear category), furniture and parts (furniture category), electrical machinery (motor-related), and telecommunications equipment (communications-related) as the main categories, which are the primary export categories of their manufacturing sectors. Additionally, some companies relocating from China to Southeast Asia will increase China's exports to ASEAN, as these companies still require key raw materials and advanced equipment from China.

The Hainan Free Trade Port should leverage its advantageous geographical location and unique policy advantages to actively integrate into this supply chain, guiding logistics and capital flows to aggregate and transit through Hainan, thereby playing the role of a platform connecting the domestic and international economic cycles. On one hand, Hainan can undertake transshipment processing and consolidation services for ASEAN products heading north to China's mainland and Japan/South Korea, fully leveraging existing policies such as the 30% tariff exemption on value-added processing to reduce corporate costs. On the other hand, Hainan can also serve as a cross-border duty-free warehousing and distribution platform for domestic products bound for ASEAN, integrating various elements to uniformly target the ASEAN market. As the convergence point of the “two major economic cycles,” Hainan must first fully leverage the appeal of China's massive domestic market to encourage ASEAN enterprises to establish a foothold in Hainan as a gateway to the Chinese market. Second, Hainan should utilize its unique “within the country but outside the customs zone” status as a bridge connecting international economic cycles, develop a distinctive industrial system, and effectively participate in global supply chain operations.

III. Analysis of the impact of the Hainan Free Trade Port on the supply chain

III. A. The Impact of Blockchain on Supply Chains

III. A. 1) The Impact of Blockchain Adoption on Corporate Profits

First, let's look at a special case where the construction cost of blockchain is sufficiently low. In this case, the impact of introducing blockchain on corporate profits is as shown in Proposition 3.

Proposition 3: When the construction cost of a blockchain is sufficiently small ($F \to 0$), there exist two thresholds, $0 < \alpha_1 < \alpha_1 < 1$, such that $\alpha_1 < \alpha < \alpha_1$ then introducing blockchain technology can increase the company's profits, i.e., $\pi_B^* > \pi_N^*$; otherwise, introducing blockchain technology will reduce the company's profits, i.e., $\pi_B^* < \pi_N^*$

The impact of α on quality improvement efforts is shown in Figure 1. At this point, the increase in corporate revenue is insufficient to offset the construction costs of introducing blockchain, leading to a decrease in profits. Only when the weight of quality improvement efforts is moderate can the introduction of blockchain incentivize fresh produce suppliers to significantly increase their quality improvement efforts, resulting in revenue increases exceeding the costs of introducing blockchain and ultimately leading to an increase in corporate profits.

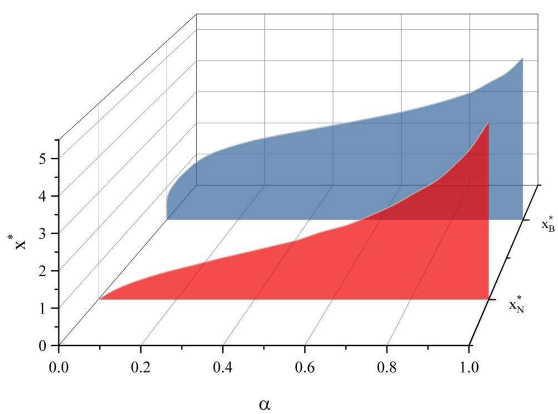


Figure 1: The impact of α on quality improvement efforts

Proposition 3 only examines the case where the cost of building a blockchain is sufficiently low. Below, we conduct a numerical experiment to study a more generalized case, comparing the profits of firms with and without a blockchain, as shown in Figure 2. This numerical experiment further demonstrates that even when the cost of building a blockchain is not negligible, the results of Proposition 3 still hold: introducing a blockchain can increase a firm's profits if and only if the weight of quality improvement efforts is moderate.

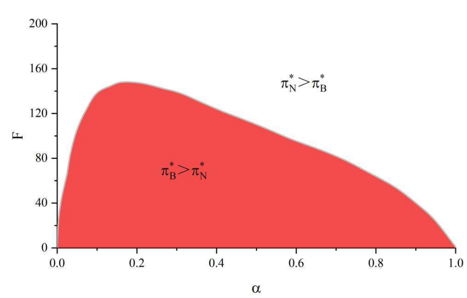


Figure 2: The Impact of blockchain on the profits of e-commerce enterprises

III. A. 2) Two companies' willingness to introduce blockchain and transfer payment mechanisms

In some cases, there is a discrepancy between the willingness of fresh produce suppliers and companies to adopt blockchain technology. Since the implementation of blockchain requires coordination and cooperation among all partners in the supply chain, it is essential to ensure that the adoption of blockchain does not harm the interests of any party involved. This will enable the smooth implementation of blockchain technology. The following analysis, based on Proposition 4, explores when the willingness of fresh produce suppliers and companies to adopt blockchain technology can align.

Proposition 4: There exists a threshold $\bar{F}_1$ such that (1) when $\alpha < \bar{\alpha}_1$ and $F > \bar{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_N^* > \pi_B^*$; (2) when $\alpha < \bar{\alpha}_1$ and $F < \bar{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_B^* > \pi_N^*$; (3) when $\alpha > \bar{\alpha}_1$ and $F > \bar{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_B^* > \pi_N^*$; (4) when $\alpha > \bar{\alpha}_1$ and $F < \bar{F}_1$, then $\prod_B^* > \prod_N^*$ and $\pi_B^* > \pi_N^*$.

The impact of introducing blockchain on the profits of the two companies is shown in Figure 3. Analysis of Proposition 4 reveals that, in certain cases, the willingness of fresh produce suppliers and companies to adopt blockchain is not aligned. Only when the construction costs of blockchain are low and the weight of quality improvement efforts is high do both parties agree to adopt blockchain, thereby achieving a “win-win” outcome. However, when the construction cost of blockchain is low and the weight of quality improvement efforts is low, or when the construction cost of blockchain is high and the weight of quality improvement efforts is high, only one company will be willing to adopt blockchain. Even when the construction cost of blockchain is high and the weight of quality improvement efforts is low, adopting blockchain will result in a “lose-lose” situation, where both the fresh produce supplier and the company's profits are harmed by the adoption of blockchain. Below, we will explain the four scenarios that appear in Proposition 4.

When the weight of quality improvement efforts is high, the quality improvement efforts of fresh produce suppliers play a key role in enhancing product value. In this case, introducing blockchain can effectively incentivize fresh produce suppliers to increase their quality improvement efforts, significantly enhancing product value and thereby increasing sales revenue. At this point, if the construction costs of blockchain are not too high, the increase in revenue can effectively offset the blockchain construction costs, thereby benefiting both fresh produce suppliers and the company. However, if the construction costs of blockchain are relatively high, although the introduction of blockchain can benefit fresh produce suppliers, the company must bear the high blockchain construction costs, so the company is unwilling to introduce blockchain at this point.

When the weight of quality improvement efforts is low, such efforts have a limited impact on product value. While introducing blockchain can incentivize fresh produce suppliers to make greater quality improvement efforts, the impact of these efforts on product value is minimal, resulting in only a modest increase in sales revenue. In this scenario, fresh produce suppliers do not benefit from blockchain adoption and thus lack the motivation to implement it. For the company, if the cost of blockchain development is relatively low, introducing blockchain can incentivize fresh produce suppliers to make greater quality improvement efforts, which remains profitable. Therefore, the company is willing to introduce blockchain, but fresh produce suppliers have no incentive to do so. However, if the cost of blockchain development is high, fresh produce suppliers cannot benefit from the introduction of blockchain either, leading to a “lose-lose” situation.

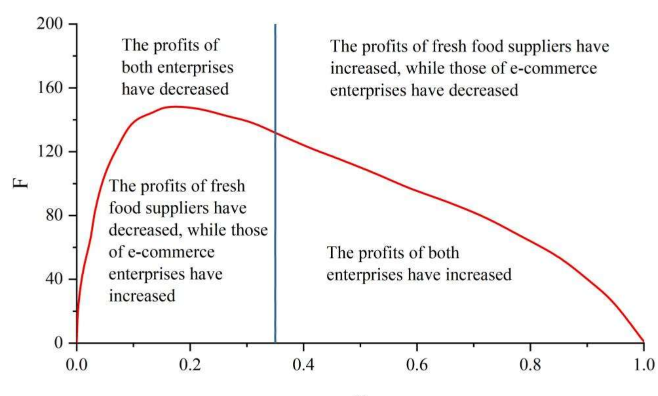


Figure 3: The impact of the introduction of blockchain on the profits of the two firms

III. B. Parameter Analysis

III. B. 1) Impact of parameter k on the profit difference before and after supply chain members participate in the blockchain network

The impact of blockchain utility on the profit difference between entities is shown in Figure 4. The quality perception utility k that blockchain technology brings to consumers is positively correlated with the profit difference between the two entities before and after participating in the blockchain. Compared to authorized processors, manufacturers have a higher threshold for participating in blockchain technology. Additionally, since manufacturers bear the full cost of introducing blockchain technology, when k is small, introducing blockchain technology is more advantageous for authorized processors. However, as k increases, the incentive to introduce blockchain technology fully compensates for the manufacturers' fixed costs, improving their profits and benefiting them more.

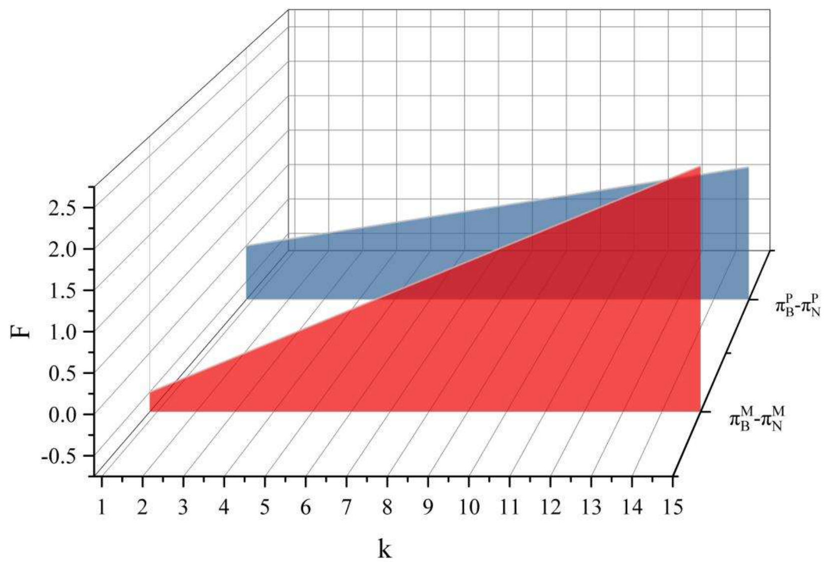


Figure 4: The impact of blockchain utility on the profit difference of entities

III. B. 2) Impact of parameter λ on the profit difference before and after supply chain members participate in the blockchain network

The parameter λ represents the manufacturer's share of the sales profit of the tiered product. The impact of the distribution ratio on the profit difference of the main entity is shown in Figure 5. The distribution ratio λ of the sales profit of the tiered product is positively correlated with the manufacturer's willingness to participate in the blockchain and negatively correlated with the willingness of the authorized processor to participate. Since manufacturers need to bear the cost of introducing blockchain technology, when λ is small, manufacturers have no incentive to introduce blockchain technology.

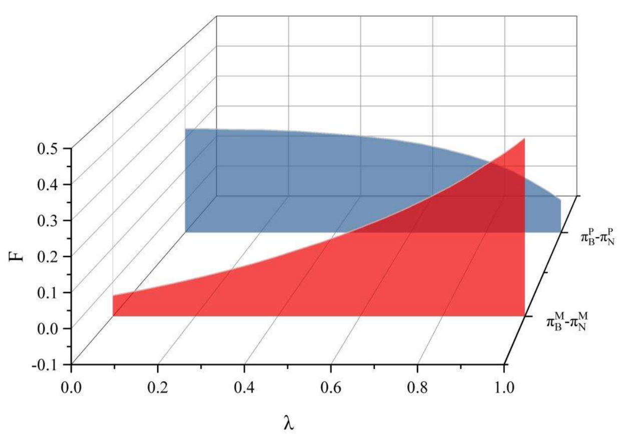


Figure 5: The effect of the split ratio on the profit margin of the subject

III. B. 3) Impact of parameter β on profits of manufacturers and authorized processors

In a tiered market, consumers have three options: (1) purchase tiered product H; (2) purchase tiered product L; (3) do not purchase. Parameter β represents the performance disadvantage of L-type products compared to H-type products. The impact of tiered product competition on the profit margin of the main entity is shown in Figure 6. When competition between the two tiered products is intense, tiered products are difficult for consumers to accept. At this point, the blockchain costs incurred by manufacturers cannot be compensated through product sales profits, and manufacturers have no incentive to participate in blockchain. However, when competition between the two tiered products is relatively mild, there is consumer demand for tiered products in the market, and the manufacturer's cost investments may be compensated through sales revenue. Additionally, since the introduction of blockchain technology helps improve consumer payment willingness and market scale, the manufacturer has an incentive to participate in blockchain to achieve greater returns.

For authorized processors, since the introduction of blockchain improves consumers' perception of the quality and utility of tiered products and expands the demand scale for tiered products, and since the costs of introducing blockchain are always borne by upstream manufacturers, the profits in Scenario B are always greater than those in Scenario N.

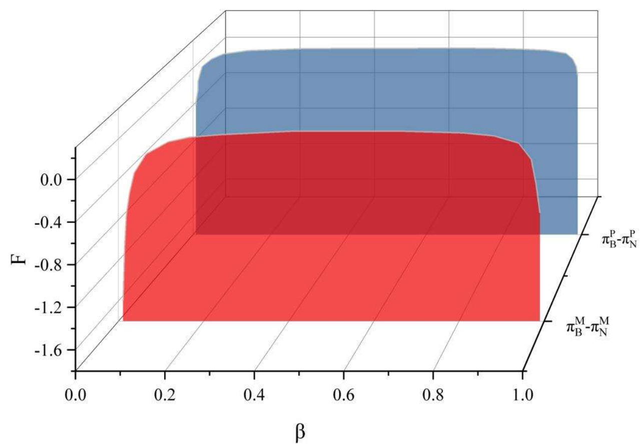
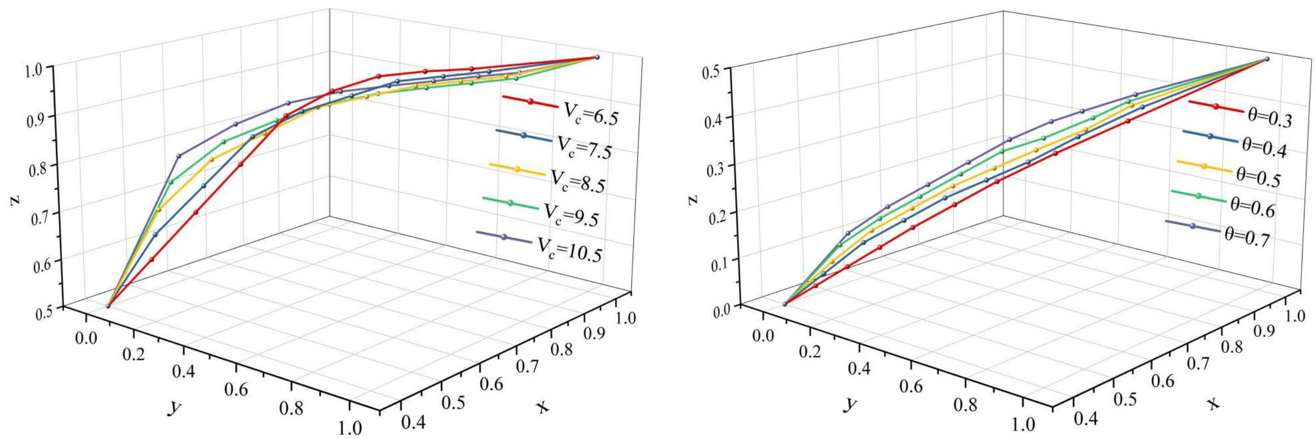


Figure 6: The effect of the degree of competition on the profit margin of the subject

III. C. Analysis of the Impact of Government Strategies on Evolutionary Stable Strategies

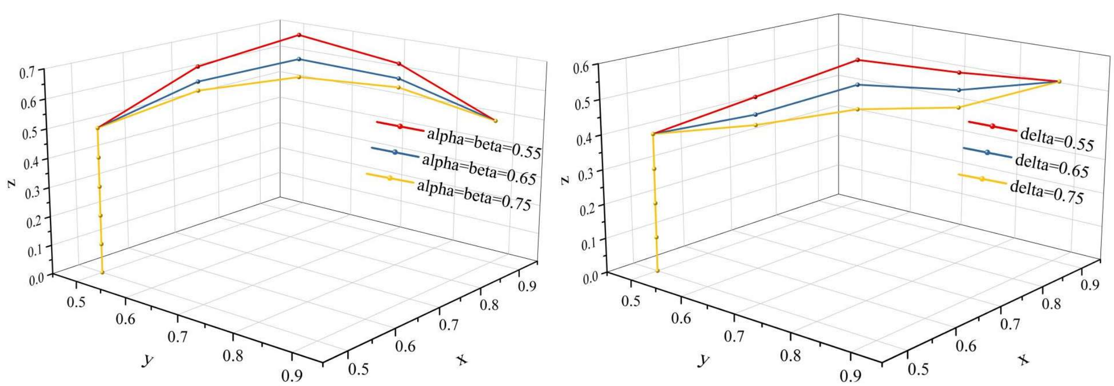
For consumers, to investigate the impact of different product values and government subsidy levels on their purchasing behavior for enterprise blockchain products, first, the selling price P is kept constant, and the product value Vc is set to be greater than P, specifically 6.5, 7.5, 8.5, 9.5, and 10.5. To eliminate the interference of government policy factors, θS is set to 0. Second, to ensure that the thresholds for both are the same, θS is set to 6.5, 7.5, 8.5, 9.5, and 10.5, respectively. Among these, the government subsidy amount S is 15, and the implementation intensity factor θ is set to 0.3, 0.4, 0.5, 0.6, and 0.7, representing low, medium, and high government implementation intensity, respectively. To eliminate the interference of product value factors, let Vc = 0. The system evolution paths under the two scenarios are shown in Figures 7(a) and 7(b), respectively. As shown in Figure 7(a), when the product value is at a certain level, the system's ESS is characterized by active government governance, food-related enterprises joining the blockchain, and consumers purchasing. Additionally, the higher the product value, the faster consumers converge toward the "purchase" direction. Additionally, consumers' strategy choices also influence corporate strategy choices. As shown in Figure 7(b), under the same government subsidy intensity and product value, the system's ESS is characterized by active government governance, non-blockchain adoption by companies, and consumer non-purchase. Comparing Figures 7(a) and 7(b), it is evident that for consumers, product value is a stronger driver of the "purchase" strategy choice than government subsidy intensity at the same level. This indicates that, compared to the intensity of government subsidy policies, the value of blockchain-enabled products has a greater impact on consumers' purchasing intentions. Additionally, consumer demand for blockchain-enabled products has a positive promotional effect on companies' decisions to adopt blockchain strategies.



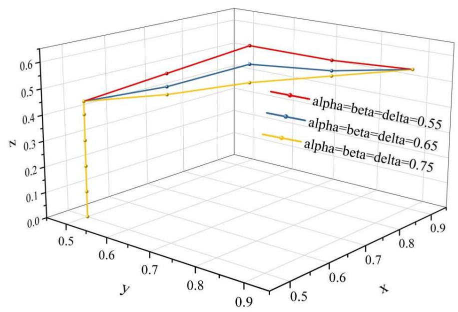
(a)Different product values (b)Different levels of government subsidies

Figure 7: Evolution path of the system

To investigate the impact of government positive guidance policies (including publicity policies and incentive policies) and punitive policies on their on-chain behavior, under the condition that the original parameters remain unchanged, A+I is randomly set to 5, and the enforcement intensity factors φ and β are set to 0.55, 0.65, 0.75. To exclude the impact of punitive policies on the experimental results, we set δ=0 to investigate the impact of positive guidance policies alone on corporate behavior under high policy enforcement intensity. The results are shown in Figure 8(a). To ensure that the thresholds for both are the same, T is set to 5, and δ is set to 0.55, 0.65, and 0.75, respectively. To exclude the influence of positive guidance policies on the experimental results, φ and β are set to 0 to investigate the impact of the government implementing only punitive policies on the behavior of food-related enterprises under high policy enforcement intensity. The results are shown in Figure 8(b). Finally, we set A+I=T=5, φ, β, and δ to 0.55, 0.65, and 0.75, respectively, to investigate the impact of simultaneously implementing positive guidance policies and punitive policies by the government on the behavior of food-related enterprises under high policy enforcement intensity. The results are shown in Figure 8(c). As shown in Figure 8, both the government's positive guidance policies and punitive policies promote enterprises' choice to adopt blockchain technology. Comparing Figures 8(a) and 8(b), it can be seen that punitive policies have a greater promotional effect on food-related enterprises' strategy selection than positive guidance policies. Additionally, Figure 8(c) indicates that in real-life scenarios, if the government can effectively combine positive incentive policies and punitive policies to guide enterprises in adopting blockchain technology, the promotional effect is superior to implementing either positive incentive policies or punitive policies alone.



(a)Positive guiding policy (b)Punishment policy



(c)Two policies

Figure 8: The impact of government policies on enterprises' on-chain behavior

IV. Conclusion

This study focuses on the construction of the supply chain ecosystem in the Hainan Free Trade Port under the digital economy and draws the following conclusions.

(1) The impact of blockchain introduction on corporate profits: When the construction cost of blockchain is sufficiently low ($F \to 0$), there are two thresholds, $0 < \underline{\alpha_1} < \overline{\alpha_1} < 1$, and blockchain introduction can increase corporate profits only when $\underline{\alpha_1} < \alpha < \overline{\alpha_1}$ is met, i.e., $\pi_B^* > \pi_N^*$; otherwise, blockchain introduction will reduce corporate profits, i.e., $\pi_B^* < \pi_N^*$. There is a threshold $\tilde{F}_1$: 1) when $\alpha < \tilde{\alpha}_1$ and $F > \tilde{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_N^* > \pi_B^*$; 2) when $\alpha < \tilde{\alpha}_1$ and $F < \tilde{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_B^* > \pi_N^*$; 3) when $\alpha > \tilde{\alpha}_1$ and $F > \tilde{F}_1$, then $\prod_N^* > \prod_B^*$ and $\pi_B^* > \pi_N^*$; 4) when $\alpha > \tilde{\alpha}_1$ and $F < \tilde{F}_1$, then $\prod_B^* > \prod_N^*$ and $\pi_B^* > \pi_N^*$.

(2) Impact of various parameters: When k is small, the introduction of blockchain technology is more advantageous for authorized distributors. However, as k increases, the incentive provided by blockchain technology to stimulate the market potential of secondary products fully compensates for the manufacturer's fixed costs, improving the manufacturer's profits and yielding greater benefits. The proportion of sales profits from tiered products, λ, is positively correlated with manufacturers' willingness to participate in blockchain technology and negatively correlated with authorized processors' willingness to participate. When competition between the two tiers of products is intense, manufacturers have no incentive to participate in blockchain technology. However, when competition between the two tiers of products is moderate, manufacturers are willing to participate in blockchain technology to achieve greater benefits.

(3) The impact of government strategies on evolutionary stable strategies: For consumers, product value is more likely to influence their choice of the “purchase” strategy than the level of government subsidies. If the government can effectively combine positive incentive policies and punitive policies to guide enterprises toward blockchain adoption, the promotional effect will be better than implementing either positive incentive policies or punitive policies alone.

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