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Analyzing Price and Profit Dynamics in Free Trade Port Supply Chains: A Blockchain-Centric Approach Under Consumer Sensitivity

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Abstract: In light of both domestic and international research on blockchain and supply chains, coupled with the blockchain development in the Hainan Free Trade Port of China, a supply chain model sensitive to demand and consumer behavior has been established. This study selects Hainan Free Trade Port and the established Hong Kong Free Trade Port for comparison. Integrating diverse tax policies of these ports, the research employs a Stackelberg game led by market pioneers to analyze fluctuations in relevant factors. The findings indicate that the incorporation of blockchain technology impacts the sales prices within supply chains. Furthermore, the utilization of blockchain significantly mitigates the influence of other variables on supply chain profits. Compared to supply chains without blockchain integration, those utilizing this technology establish substantial profit advantages.

Keywords: Free Trade Port; Supply chain; Blockchain; Channel comparison

1 Introduction

Globally, the uneven development of the world economy coupled with the escalation and normalization of major trade sanctions has resulted in a contraction in the scope and increased complexity of the allocation of various production factors. These external influences have triggered significant changes in the global economic landscape, accelerating both global manufacturing and domestic investment, and prompting a reshaping and establishment of global supply chains [1].

Within the context of China's domestic big cycle and the dual circulation of international and domestic economies, it is imperative to clear all blockages in the cycle and eliminate barriers in the market supply and circulation of production factors and goods and services. China, having grown into the world's second-largest economy and a major manufacturing nation, has achieved the remarkable feat of comprehensively building a moderately prosperous society and is stepping into a phase of high-quality development. This transition demands higher levels of reform and deeper openness. The construction of Hainan Free Trade Port, a "new highland" of openness, aligns perfectly with China's strategic requirements for reform and opening up anew. As part of the central government and State Council's significant strategy for deepening reform and expanding openness, the construction of Hainan Free Trade Port is poised to become a new highland for domestic circulation and consumption upgrade. It is set to serve as a hub for the dual circulation supply chain and a fulcrum for global trade, enhancing China's industrial global competitiveness [2].

The complexities of globalized, diverse regulatory policies and the multiplicity of cultures and human behaviors in supply chain networks make evaluating information and managing risks within these intricate networks a near impossibility. Inefficiencies in transactions, fraud, theft, and poor supply chain performance have led to a greater deficit in trust, necessitating improved information sharing and verifiability. Traceability is becoming an increasingly urgent requirement, particularly notable in industries such as agriculture, food, pharmaceuticals, medical, and high-value goods. The origins of luxury and valuable items, often reliant on paper certificates and receipts, are easily lost or altered. Indeed, the lack of transparency in the supply value of any commodity hinders the ability of supply chain entities and customers to authenticate and verify the real value of that commodity. The cost, reliability, and transparency of intermediaries make the management of traceability in supply chains even more complex [3]. Blockchain technology, as a disruptive core data technology, with its distributed digital ledger ensuring transparency, traceability, and security, addresses the shortcomings in the development of supply chains. It mitigates the prevalent information asymmetry in the trade of various raw materials, semi-finished, or finished products and alleviates management issues within supply chains.

In the field of blockchain technology's impact on supply chain decisions, international scholars have primarily focused on its influence on traditional supply chain goals, customer stickiness, traceability, transaction costs, and social welfare.

Sara Saberi posits that blockchain could be a disruptive technology in the design, organization, operation, and general management of supply chains. The ability of blockchain to guarantee information reliability, traceability, and authenticity, along with smart contract relationships in untrusted environments, heralds a significant rethinking of supply chains and their management [3]. de Sousa Jabbour et al. [4] highlights that supply chain practices and strategies are also facing pressures to consider and certify supply chain sustainability. Sustainability is defined as a triple bottom line concept, entailing a balance of environmental, social, and commercial dimensions in managing supply chains. In their supply chain finance analysis, Rodrigues et al. [5] suggest that Bitcoin, as a successful financial technology, has paved the way for the application of blockchain in supply chains. They discuss from a technological perspective how and under what conditions blockchain can become a successful use case. Karl and Gervais [6] express that there is no universal formula to determine the relevance of blockchain without a detailed analysis of its different attributes and types, the needs and objectives of potential participants, and specific characteristics of the application itself. Especially in large enterprises where there is a lack of trust internally, blockchain technology is needed to validate their business operations. Kwark et al. [7] states that quality information plays starkly different roles in the competition of different supply chains. A retailer's ability to benefit from third-party information depends on the choice of pricing scheme, the accuracy of third-party information, and the relative importance of quality and timing attributes in consumer product evaluations. Kamblea et al. [8] notes that by eliminating issues related to trust, blockchain technology companies offer various benefits. Blockchain technology is expected to improve the sustainable performance of agricultural supply chains by eliminating a large number of intermediary institutions.

Tian et al. [9] provided a comprehensive solution for the integrity, authenticity, and transparency of product information in the supply chain by utilizing blockchain technology in the field of supply chain management, providing useful guidance for the application and development of blockchain in supply chain management. Chen [10] stated that logistics and supply chain management are considered areas where blockchain is very suitable for application. Miao [11] starts from the perspective of blockchain in logistics, integrates blockchain technology throughout the entire logistics process, and helps consumers and logistics enterprises solve the real-time trend problems of logistics products that are widely concerned. Zhao et al. [12] analyzed from the perspective of the shipping supply chain that when the system structure is centralized, the application of blockchain technology can peak the demand for the sinking market of enterprises. Research on Hainan's supply chain shows that China is gradually turning Hainan Free Trade Port into a front-end warehouse for the international supply chain, integrating and improving the upstream of the supply chain, optimizing the logistics supply chain architecture [13]. At the same time, from a global geographical perspective, Hainan's transportation hub plays a significant role [14]. The total land area of the province accounts for about half of the national tropical and subtropical land area, and the cultivated land area accounts for one-fifth of the total land area of the province [15]. However, there are serious problems with information differentiation, single transaction methods, and complex intermediate links in agriculture in Hainan Province, which seriously damage the interests of farmers and consumers [16]. With the widespread application of blockchain technology, Tian [17] utilized Radio Frequency Identification (RFID) and blockchain technology to construct a new agricultural supply chain traceability system based on RFID and blockchain technology, aiming to optimize supply chain management and match the best transportation routes. With the impact of the COVID-19 in 2020, most groups planning to go abroad to enjoy medical services have become potential customers of medical tourism in Hainan [18]. Although Hainan has policy advantages and development opportunities in developing medical tourism, due to the incomplete medical tourism management system, the industrial chain and supply chain are not matched, and relevant medical service centers cannot be connected [19]. Currently, the development of new digital platforms and services using blockchain technology has become a research focus in the fields of finance and electronic finance [20, 21]. The zero tariff policy of the free trade port has also contributed to the vigorous development of Hainan Free Trade Port. With the steady progress of the free trade port construction process, the products and industries included in the duty-free list will gradually increase [22]. In the face of the continuous strengthening of foreign investment protection in the development of international investment rules, as well as the problems in the government's compliance with commitments and the construction of comment mechanisms for foreign-invested enterprises, it is necessary to improve the relevant systems for foreign investment protection in Hainan Free Trade Port [23].

In the construction of Hainan Free Trade Port, tax issues are the primary concern of import and export enterprises, directly impacting their costs and supply chain construction choices. To explore the combination of supply chain and blockchain in the context of Hainan Free Trade Port, the development of existing supply chain networks in Hainan is surveyed. Combined with the overall plan for the construction of data elements in the Free Trade Port, the tax policies of other free trade zones and ports are compared. In the channel supply chain system, parameters such as consumer sensitivity coefficients to product clearance inspection and receipt time, and blockchain unit verification fees, are introduced. Under two scenarios, with and without the use of blockchain technology, a mathematical model is established using the basic framework of a manufacturer-led Stackelberg game analysis and the basic demand-supply (D-S) model. This model analyzes the impact of various factors on sales prices and profits in the supply chains of cross-border e-commerce enterprises under the drive of blockchain technology.

2 Model Description and Assumptions

2.1 Model Description

The theoretical foundation for model construction is laid based on the discussion of both domestic and international research and the basic situation of the supply chain in Hainan. Additionally, there is limited literature that combines the application of blockchain in supply chains with the special tax rates of free trade ports. Therefore, this model selects Hainan Free Trade Port and the established Hong Kong Free Trade Port for comparison. Building on the different tax policies of these two ports, blockchain-specific parameters such as consumer sensitivity to the time required for product clearance inspection and the likelihood of product authentication being false, and the unit cost of using blockchain technology for verification, are introduced to construct the free trade port supply chain model. The optimal pricing and channel selection strategies under different models are obtained through a Stackelberg game analysis led by market pioneers.

In the supply chains of the two ports' different channels, it is considered that both import the same type of goods, which meet the respective port's tax incentive policies. When introducing tax issues, the Hainan Free Trade Port calculates profits using income tax, while the Hong Kong Free Trade Port uses profit tax. The calculations only consider the effects of wholesale price, sale price, and demand. Depending on whether blockchain technology is adopted, the models are divided into three scenarios: the original model with no blockchain technology (NC model), the advanced model with blockchain technology (YC model), and the solo model with only Hainan Free Trade Port using blockchain technology (SC model). The structural diagrams are shown in Figure 1, Figure 2 and Figure 3.

NC Model: Both ports maintain traditional supply chain channels. In this model, due to Hong Kong Free Trade Port's reliance on established procedures, it clears customs before Hainan. After clearance, it independently decides the retail price of the product and proceeds to direct sales. Hainan, following its post-clearance checks, sets its prices based on those established by Hong Kong and then sells.

YC Model: Both ports apply blockchain technology to their supply chain channels. Since both utilize blockchain technology, but with Hong Kong Free Trade Port still leading due to its mature processes, it clears customs before Hainan. After clearance, Hong Kong independently decides the retail price for direct sales. Post-clearance, Hainan sets its prices based on Hong Kong's and proceeds to sell.

SC Model: Hainan Free Trade Port applies blockchain technology to its supply chain channel, while Hong Kong Free Trade Port does not. As the former uses blockchain technology, it optimizes the entire process. Hainan's customs clearance speed surpasses that of Hong Kong. After clearance, Hainan decides the retail price first and proceeds with direct sales. Once Hong Kong completes its checks, it sets its prices based on those determined by Hainan and then sells.

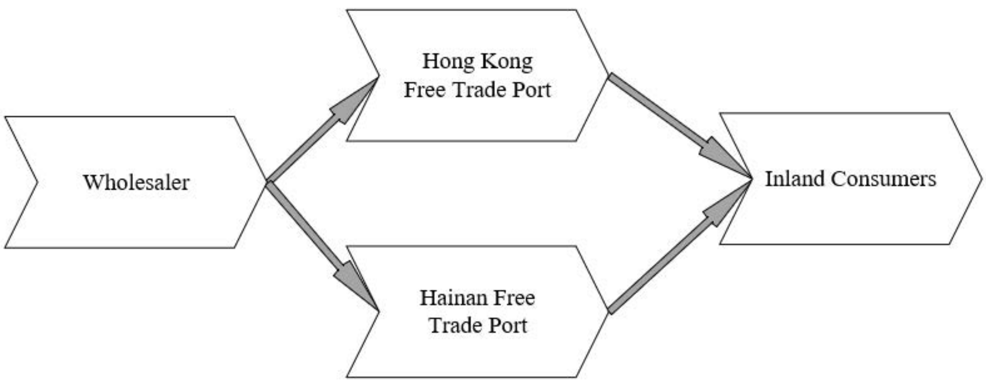

Figure 1. Original model without blockchain technology (NC Model)

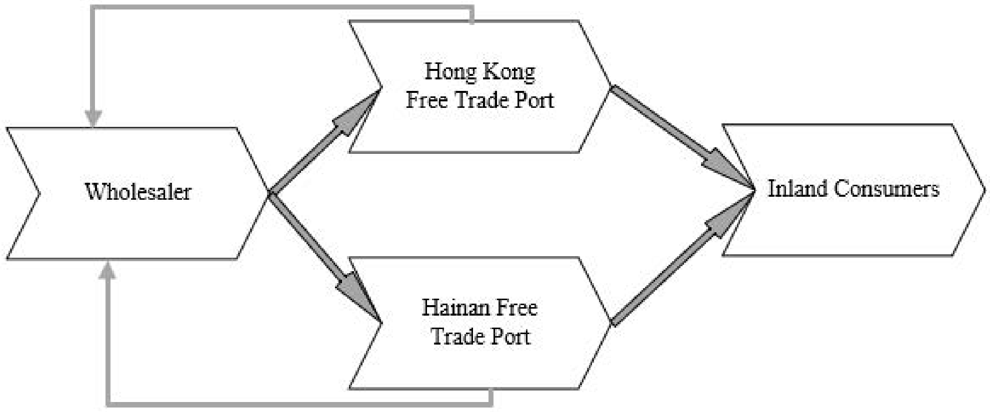

Figure 2. Advanced model with blockchain technology (YC Model)

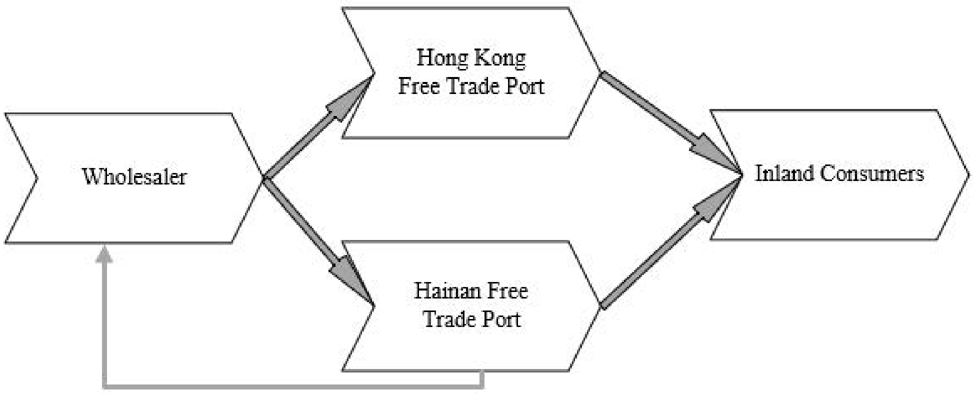

Figure 3. Solo model with Hainan Free Trade Port using blockchain technology (SC Model)

2.2 Assumptions

Based on the above description and combined with the policy requirements of Hainan Free Trade Port, the following assumptions are proposed:

(1) a represents the potential demand for the specified product entering the inland market.

(2) $\mathrm{b}(0 < \mathrm{b} < 1)$ represents the cross-price elasticity coefficient generated during pricing by both ports.

(3) The product clearance approval and inspection assessment involve time consumption. Without the use of blockchain technology, the time required for product clearance approval and inspection assessment is t. With blockchain technology, the required time is T, and $t > T$.

(4) Without the use of blockchain technology, there is a certain probability that the product is counterfeit. Let e represent the probability of blockchain product detection being accurate. Hence, $1 - e$ represents the probability of being counterfeit. With the introduction of blockchain technology, the authenticity of the product is guaranteed, i.e., no counterfeit products, with e approaching 1.

(5) The sensitivity coefficient of consumers to the entire clearance inspection process time is denoted by β; the sensitivity coefficient of consumers to the authenticity of the product when blockchain technology is not used is denoted by γ.

(6) With the use of blockchain technology, the unit verification cost incurred by the wholesaler for using blockchain technology is represented as f.

(7) w represents the unit cost price of the product at the time of port entry.

(8) p represents the retail price after port exit.

(9) The profit tax rate for the Hong Kong Free Trade Port is 16.5%, and the income tax rate for the Hainan Free Trade Port is 15%.

(10) To ensure the model's rationality and that all supply chain participants can profit, the potential demand must always be greater than the demand affected by time and authenticity sensitivity.

3 Model Calculation

3.1 NC Model

In this model, Hong Kong Free Trade Port, as an established Free Trade Port with advanced processing technology and procedures, has a faster clearance speed than Hainan Free Trade Port. Therefore, it follows a two-stage Stackelberg game. In the first stage, after receiving the wholesale price, the wholesaler processes it, and the Hong Kong Free Trade Port, upon limited processing completion, sets the sale price $\mathrm{P_X}$. In the second stage, after processing by the Hainan Free Trade Port, it sets the sale price P_h based on Hong Kong's price.

Demand function for the Hong Kong Free Trade Port channel:

$$\mathrm{D_X = a - P_X + b^*P_h - A_X} \tag{1}$$

Demand function for the Hainan Free Trade Port channel:

$$D_h = a - P_h + b^*P_x - A_h \tag{2}$$

For simplification, let: $A_h = \beta^*t_h - \gamma^*(1-e); A_x = \beta^*t_x - \gamma^*(1-e)$.

Profit function for the Hong Kong Free Trade Port channel:

$$\pi_\mathrm{X} = \mathrm{(P_X - w)^*\, D_X^*(1 - 16.5\%)} \tag{3}$$

Profit function for the Hainan Free Trade Port channel:

$$\pi_\mathrm{h} = \mathrm{(P_h - w)^*\, D_h - 0.15^*P_h{}^*D_h} \tag{4}$$

Using the backward induction method of the Stackelberg game for calculation:

Insert (1) into (3) to obtain the function of π_X with respect to $\mathrm{P_X}$. When the first-order partial derivative of π_X with respect to $\mathrm{P_X}$ is zero, the maximum profit is obtained, which is the equilibrium sale price for the Hong Kong Free Trade Port (5).

$$\mathrm{P_X = a/2 - A_X/2 + w/2 + (P_h^*\, b)/2} \tag{5}$$

Inserting (5) and (2) into (4), replacing the original $\mathrm{P_X}$ and $\mathrm{D_h}$ in the formula to obtain the function of π_h with respect to $\mathrm{P_H}$. When the first-order partial derivative of π_h with respect to $\mathrm{P_H}$ is zero, the maximum profit is obtained, which is the equilibrium sale price for the Hainan Free Trade Port. Then, based on this sale price, the sale price for the Hong Kong Free Trade Port and the profits of both ports are calculated, see Eqs. (6)-(9).

$$\begin{aligned}\mathrm{P_h} = &-\mathrm{(34^*a - 34^*\, A_h + 40^*w - 17^*\, A_x^*\, b + 17^*a^*\, b +}\\ &\mathrm{17^*\, b^*w - 20^*\, b \wedge 2^*w)/\big(34^*\,(\, b\hat{}2 - 2)\big)}\end{aligned} \tag{6}$$

$$\begin{aligned}\mathrm{P_x} = &\mathrm{(68^*\, A_x - 68^*a - 68^*w + 34^*\, A_h^*\, b - 34^*a^*\, b}\\ &\mathrm{-40^*\, b^*w - 17^*\, A_x^*\, b\hat{}2 + 17^*a^*\, b\hat{}2 + 17^*\, b\hat{}2^*w + 20^*\, b\hat{}3^*w\big)/(68^*(\, b \wedge 2 - 2))}\end{aligned} \tag{7}$$

$$\begin{aligned}\pi_\mathrm{X} = &\mathrm{(167^*\,(68^*\, A_x - 68^*a + 68^*w + 34^*\, A_h^*\, b - 34^*a^*\, b - 40^*\, b^*w}\\ &\mathrm{-17^*Ax^*\, b\hat{}2 + 17^*a^*\, b\hat{}2 - 51^*\, b\hat{}2^*w + 20^*\, b\hat{}3^*w)\hat{}\, 2\big)/\Big(924800^*\,(\, b\hat{}2 - 2)\hat{}\, 2\Big)}\end{aligned} \tag{8}$$

$$\begin{aligned}\pi_\mathrm{h} = &-\mathrm{((a - A_h - (20^*w)/17 - (Ax^*\, b)/2 + (a^*\, b)/2 + (b^*w)/2}\\ &\mathrm{+ \big(10^*\, b\hat{}2^*w\big)/17)^*\,(34^*a - 34^*\, A_h - 40^*w - 17^*Ax^*\, b + 17^*a^*\, b}\\ &\mathrm{+17^*\, b^*w + 20^*\, b\hat{}2^*w)\big)/\big(80^*\,(\, b\hat{}2 - 2)\big)}\end{aligned} \tag{9}$$

3.2 YC Model

In this model, both ports utilize blockchain technology. However, Hong Kong, with its foundation as an established free trade port, still processes faster than Hainan Free Trade Port. Thus, it follows a two-stage Stackelberg game. In the first stage, after receiving the wholesale price, the wholesaler processes it, and the Hong Kong Free Trade Port, being the first to process, sets the sale price $\mathrm{P_X}$. In the second stage, after processing by the Hainan Free Trade Port, it sets the sale price Ph based on Hong Kong's price. Additionally, due to the use of blockchain technology, there are no counterfeit products in this model, so the sensitivity to authenticity is not factored into the calculations.

Demand function for the Hainan Free Trade Port channel:

$$D_h = a - P_h + b^* P_x - A_h \tag{10}$$

Demand function for the Hong Kong Free Trade Port channel:

$$D_X = a - P_x + b^* P_h - A_x \tag{11}$$

For simplification, let: $A_h = \beta^* T_h; \quad A_x = \beta^* T_x$.

Profit function for the Hong Kong Free Trade Port channel:

$$\pi_{\mathrm{X}} = (\mathrm{P_X} - \mathrm{w} - \mathrm{f})^* \, \mathrm{D_X^*}(1 - 16.5\%) \tag{12}$$

Profit function for the Hainan Free Trade Port channel:

$$\pi_{\mathrm{h}} = (\mathrm{P_h} - \mathrm{w})^* \, \mathrm{D_h} - 0.15^* \mathrm{P_h}^* \mathrm{D_h} - \mathrm{f}^* \mathrm{D_h} \tag{13}$$

Using the backward induction method of the Stackelberg game for calculation:

Insert (11) into (13) to obtain the function of π_{X} with respect to $\mathrm{P_X}$. When the first-order partial derivative of π_{X} with respect to $\mathrm{P_X}$ is zero, the maximum profit is obtained, which is the equilibrium sale price for the Hong Kong Free Trade Port (14).

$$P_X = a/2 - A_X/2 + f/2 + w/2 + (P_h^* b)/2 \tag{14}$$

Inserting (14) and (10) into (12), replacing the original $\mathrm{P_X}$ and $\mathrm{D_h}$ in the formula to obtain the function of π_{H} with respect to PH. When the first-order partial derivative of π_{H} with respect to $\mathrm{P_H}$ is zero, the maximum profit is obtained, which is the equilibrium sale price for the Hainan Free Trade Port. Then, based on this sale price, the sale price for the Hong Kong Free Trade Port and the profits of both ports are calculated, see Eqs. (15)-(18).

$$\begin{aligned}\mathrm{P_x} = {} & \mathrm{a/2 - A_x/2 + f/2 + w/2 - (b^* \left((17^*a)/20 - (17^* \, A_h)/20 - (17^* \, A_x^* \, b)/40 + \right.} \\ & \mathrm{(17^*a^* \, b)/40 + (17^* \, b^*f)/40 + (17^* \, b^*w)/40 - ((b\hat{\ }2 - 2)^* \, (20^*f +} \\ & \mathrm{\left. 20^*w))/40)) / \left(2^* \left(\left(17^* \, b\hat{\ }2\right)/20 - 17/10\right)\right)}\end{aligned} \tag{15}$$

$$\begin{aligned}\mathrm{P_h} = {} & \mathrm{-((17^*a)/20 - (17^* \, A_h)/20 - (17^* \, A_x^* \, b)/40 + (17^*a^* \, b)/40 + (17^* \, b^*f)/40} \\ & \mathrm{+(17^* \, b^*w)/40 - \left((b\hat{\ }2 - 2)^* \, (20^*f + 20^*w)\right)/40\Big) / \left(\left(17^* \, b\hat{\ }2\right)/20 - 17/10\right)}\end{aligned} \tag{16}$$

$$\begin{aligned}\pi_{\mathrm{X}} = {} & \mathrm{(167^* \, (68^* \, A_x - 68^*a + 68^*f + 68^*w + 34^* \, A_h^* \, b - 34^*a^* \, b - 40^* \, b^*f} \\ & \mathrm{- 40^* \, b^*w - 17^* \, A_x^* \, b\hat{\ }2 + 17^*a^* \, b\hat{\ }2 - 51^* \, b\hat{\ }2^*f + 20^* \, b\hat{\ }3^*f} \\ & \mathrm{-51^* \, b\hat{\ }2^*w + 20^* \, b\hat{\ }3^*w)\hat{\ }2\Big) / \left(924800^* \, \left(b\hat{\ }2 - 2\right)\hat{\ }2\right)}\end{aligned} \tag{17}$$

$$\begin{aligned}\pi_{\mathrm{h}} = {} & \mathrm{-((34^*a - 34^* \, A_h - 40^*f - 40^*w - 17^* \, A_x^* \, b + 17^*a^* \, b + 17^* \, b^*f + 17^* \, b^*w} \\ & \mathrm{+20^* \, b\hat{\ }2^*f + 20^* \, b\hat{\ }2^*w)^* \, (a - A_h - (20^*f)/17 - (20^*w)/17 - (A_x^* \, b)/2 +} \\ & \mathrm{(a^* \, b)/2 + (b^*f)/2 + (b^*w)/2 + \left(10^* \, b\hat{\ }2^*f\right)/17 + \left(10^* \, b\hat{\ }2^*w\right)/17)\Big) / \Big(80^* \, (b\hat{\ }^2 - \; 2))}\end{aligned} \tag{18}$$

3.3 SC Model

In this model, only the Hainan Free Trade Port utilizes blockchain technology. Consequently, leveraging blockchain technology, Hainan's clearance speed surpasses that of the Hong Kong Free Trade Port. This model still follows a two-stage Stackelberg game. In the first stage, after receiving the wholesale price, the Hainan Free Trade Port, being the first to process, sets the sale price P_h. In the second stage, after processing by the Hong Kong Free Trade Port, it sets the sale price $\mathrm{P_X}$ based on Hainan's price. As Hainan uses blockchain technology, there are no counterfeit products for its exports, meaning sensitivity to authenticity is not factored into its calculations, but it is considered for the Hong Kong Free Trade Port.

Demand function for the Hong Kong Free Trade Port channel:

$$\mathrm{D_X = a - P_X + b^*P_h - A_X} \tag{19}$$

Demand function for the Hainan Free Trade Port channel:

$$D_h = a - P_h + b^*P_X - A_h \tag{20}$$

For simplification, let: $A_h = \beta^*T_h; \quad A_x = \beta^*t_x - \gamma^*$ (1-e).

Profit function for the Hong Kong Free Trade Port channel:

$$\mathrm{\pi_X = (P_X - w)^*\, D_X^*(1 - 16.5\%)} \tag{21}$$

Profit function for the Hainan Free Trade Port channel:

$$\mathrm{\pi_h = (P_h - w)^*\, D_h - 0.15^*P_h^*D_h - f^*D_h} \tag{22}$$

Using the backward induction method of the Stackelberg game for calculation:

Insert (20) into (22) to obtain the function of π_h with respect to P_h. When the first-order partial derivative of π_h with respect to P_h is zero, the maximum profit is obtained, which is the equilibrium sale price for the Hainan Free Trade Port (23).

$$\mathrm{P_h = a/2 - A_h/2 + (10^*f)/17 + (10^*w)/17 + (P_X^*\, b)\,/2} \tag{23}$$

Inserting (23) and (19) into (21), replacing the original P_h and $\mathrm{D_x}$ in the formula to obtain the function of π_x with respect to P_x. When the first-order partial derivative of π_x with respect to P_x is zero, the maximum profit is obtained, which is the equilibrium sale price for the Hong Kong Free Trade Port. Then, based on this sale price, the sale price for the Hainan Free Trade Port and the profits of both ports are calculated, see Eqs. (24)-(27).

$$\begin{aligned}\mathrm{P_x} &= \mathrm{((167^*\ A_x)\,/200 - (167^*a)/200 - (167^*b^*\ (a/2 - A_h/2 + (10^*f)/17+} \\ &\mathrm{(10^*w)/17))/200 + (167^*w^*(\ b\hat{\ }2/2 - 1))/200)/((167^*\ b\hat{\ }2)/200 - 167/100)}\end{aligned} \tag{24}$$

$$\begin{aligned}\mathrm{P_h} = \big(&\mathrm{68^*\ A_h - 68^*a - 80^*f - 80^*w + 34^*\ A_x^*\, b - 34^*a^*\ b - 34^*\ b^*w - 17^*\ A_h{}^*\ b\hat{\ }2} \\ &\mathrm{+17^*a^*\ b\hat{\ }2 + 20^*\ b\hat{\ }2^*f + 20^*\ b\hat{\ }2^*w + 17^*\ b\hat{\ }3^*w\big)\,/\,\big(68^*\,(\ b\hat{\ }2 - 2)\big)}\end{aligned} \tag{25}$$

$$\begin{aligned}\mathrm{\pi_h} = &\mathrm{-\,(167^*\ (a/2 - A_x/2 - w/2 - (A_h^*\ b)\,/4 + (a^*\ b)/4 + (5^*\ b^*f)/17 + (5^*\ b^*w)/17} \\ &\mathrm{+\,(}b\mathrm{\hat{\ }2^*w)\,/4)^*\ (34^*a - 34^*\ A_x - 34^*w - 17^*\ A_h{}^*\ b + 17^*a^*\ b + 20^*\ b^*f + 20^*\ b^*w} \\ &\mathrm{+17^*\ b\hat{\ }2^*w)\big)\,/\,\big(6800^*\,(\ b\hat{\ }2 - 2)\big)}\end{aligned} \tag{26}$$

$$\begin{aligned}\mathrm{\pi_X} = \Big(&\mathrm{((17^*A_h)/3 - (17^*a)/3 + (20^*f)/3 + (20^*w)/3 - (17^*b^*w)/3)^*\ (A_h/3 - a/3+} \\ &\mathrm{(20^*f)\,/51 + (20^*w)\,/51 - (b^*w)/3))\,/20 + ((A_h/3 - a/3 + (20^*f)\,/51 + (20^*w)\,/51-} \\ &\mathrm{(b^*w)/3)^*\ (2839^*\ A_h - 2839^*a + 3340^*f + 3340^*w - 2839^*\ b^*w))\,/(10200^*\ b)}\end{aligned} \tag{27}$$

4 Numerical Analysis

4.1 NC Model

4.1.1 Calculation results

Hong Kong Free Trade Port:

$$\frac{\partial Px}{\partial \beta} = (4 - b^\wedge 2)\, t_x + 2bt_h/4\,(b^\wedge 2 - 2) < 0,$$

$$\frac{\partial Px}{\partial \gamma} = (4 + 2b - b^\wedge 2)\,(1 - e)/4\,(b^\wedge 2 - 2) < 0,$$

$$\frac{\partial \pi x}{\partial \beta} = \mu\,[(4 - b^\wedge 2)\, t_x + 2bt_h] < 0,$$

μ is the coefficient after derivation and $\mu < 0$, similarly $\frac{\partial \pi \mathrm{X}}{\partial y} < 0$.

Hainan Free Trade Port:

$$\frac{\partial Ph}{\partial \beta} = 2\mathrm{t_h} + \mathrm{bt_x}/4\left(\mathrm{b}^\wedge 2 - 2\right) < 0$$

$$\frac{\partial Ph}{\partial \gamma} = (2 + \mathrm{b})(1 - \mathrm{e})/4\left(\mathrm{b}^\wedge 2 - 2\right) < 0$$

$$\frac{\partial \pi \mathrm{h}}{\partial \beta} = -\,(-\mathrm{t_h} - \mathrm{t_x b}/2)\,(-34\mathrm{t_h} - 17\mathrm{bt_x})\,/\,(\mathrm{b}^\wedge 2 - 2) < 0 \text{ similarly } \frac{\partial \pi \mathrm{h}}{\partial \gamma} < 0.$$

4.1.2 Result analysis

Using numerical values inserted into the model for calculation, the impact of consumer sensitivity on supply chain sales prices and profits is analyzed sequentially. Letting $\mathrm{a} = 100,\ \mathrm{b} = 0.5, \mathrm{w} = 20, \mathrm{e} = 0.5, \mathrm{t_h} = 2, \mathrm{t_x} = 1$, and $\mathrm{A_h} = \beta^* \mathrm{t_h} - \gamma^*(1 - \mathrm{e});\quad \mathrm{Ax} = \beta^* \mathrm{t_x} - \gamma^*(1 - \mathrm{e})$, the effects of increasing consumer sensitivity coefficients to the entire clearance inspection process and product authenticity on optimal sales prices and supply chain profits are illustrated in Figure 4.

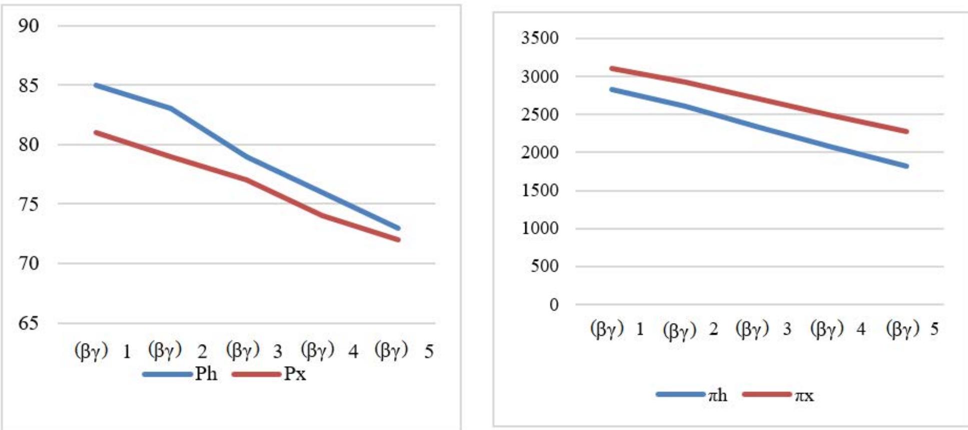

Figure 4. Impact of increased sensitivity on supply chain prices and profits

Retail Price Trends: When neither of the free trade ports, Hainan or Hong Kong, employs blockchain technology, the retail prices in both ports decrease as consumer sensitivity to both the time taken for clearance inspection and the authenticity of products increases. However, as sensitivity gradually increases, the gap in the selling prices between the two ports narrows. At a certain threshold of sensitivity, the prices in both ports will converge to be the same.

Profit Trends: As the sensitivity coefficients for the entire clearance inspection process time and product authenticity increase, the supply chain profits for both the Hong Kong and Hainan Free Trade Port channels decrease. However, the profit decline in the Hong Kong Free Trade Port channel is more stable compared to that in the Hainan Free Trade Port channel. Furthermore, the gap in profits between the two ports is observed to widen progressively.

4.2 YC Model

4.2.1 Calculation results

Hong Kong Free Trade Port:

$\frac{\partial Px}{\partial \beta} = \left(20\,\mathrm{T_x}/17 + \mathrm{t_h} + \mathrm{bT_x}/2\right)/2\left(\mathrm{b}^\wedge 2 - 2\right) < 0$

$\frac{\partial Px}{\partial f} = \left(-1/2 - 17/40\,\mathrm{b} + \left(\mathrm{b}^\wedge 2 - 2\right)\mathrm{f}/2\right)/40\left(2^*\left(\left(17^*\,\mathrm{b}^\wedge 2\right)/20 - 17/10\right)\right) > 0$

$\frac{\partial \pi \mathrm{X}}{\partial \beta} = \mu\left[\left(4 - \mathrm{b}^\wedge 2\right)\mathrm{T_x} + 2\,\mathrm{b}\,\mathrm{T_h}\right] < 0, \mu$ is the coefficient after derivation and $\mu < 0$

$\frac{\partial \pi \mathrm{X}}{\partial f} = \left(68 - 40\,\mathrm{b} - 51\,\mathrm{b}^\wedge 2 + 20\,\mathrm{b}^\wedge 3\right)/\left(924800^*\left(\mathrm{b}^\wedge 2 - 2\right)^\wedge 2\right)$, in certain ranges, b makes $\frac{\partial \pi \mathrm{X}}{\partial f} < 0$, and in others, $\frac{\partial \pi \mathrm{X}}{\partial f} > 0$.

Hainan Free Trade Port:

$\frac{\partial Ph}{\partial \beta} = 2\,\mathrm{T_h} + \mathrm{bT}_x/2\left(\mathrm{b}^\wedge 2 - 2\right) < 0$

$\frac{\partial Ph}{\partial f} = \left(-17\,\mathrm{b}/40 + \left(\mathrm{b}^\wedge 2 - 2\right)/2\right)/\left(\left(17^*\,\mathrm{b}^\wedge 2\right)/20 - 17/10\right) > 0$

$\frac{\partial \pi \mathrm{h}}{\partial \beta} = \frac{\partial(34\mathrm{Ah} + 17\mathrm{bAx})(\mathrm{Ah} + \mathrm{bAx}/2)/-80\left(\mathrm{b}^\wedge 2 - 2\right)}{\partial \beta} < 0$

$\frac{\partial \pi \mathrm{h}}{\partial f} = \frac{\partial\left(-40\mathrm{f} + 17\mathrm{bf} + 20\,\mathrm{b}^\wedge 2\mathrm{f}\right)\left(-\frac{17\mathrm{f}}{20} + \frac{\mathrm{bf}}{2} + \frac{10b^2 f}{17}\right)/-80\left(\mathrm{b}^\wedge 2 - 2\right)}{\partial f}$, in certain ranges, b makes $\frac{\partial \pi \mathrm{h}}{\partial f} < 0$, and in others, $\frac{\partial \pi \mathrm{h}}{\partial f} > 0$.

4.2.2 Result analysis

Using numerical values inserted into the model, the impact of consumer sensitivity to the entire clearance inspection process time and verification costs on the optimal sales prices and supply chain profits is analyzed. Letting $a = 100, b = 0.5, w = 20, e = 0.5, T_h = 2, T_x = 1$, and $A_h = \beta^* Th; Ax = \beta^* Tx$, the effects are illustrated in Figure 5. Moreover, combining with Model 1, a comparison of supply chain profits under the same sensitivity with and without the application of blockchain technology is shown in Figure 6.

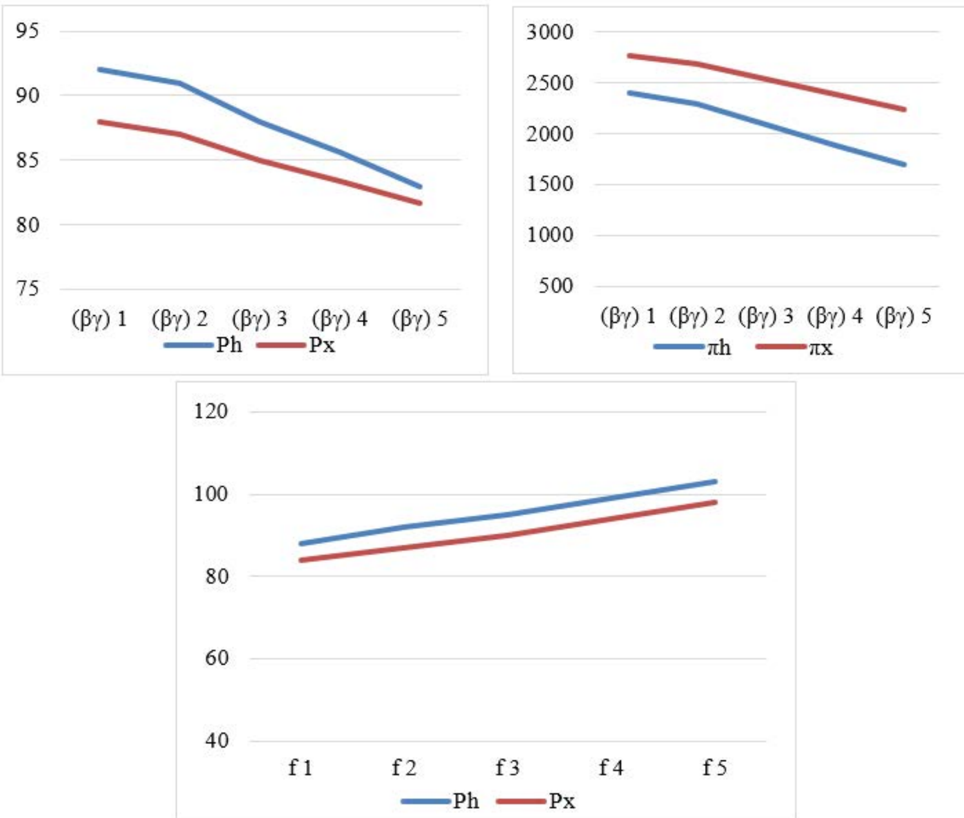

Figure 5. Impact of increased sensitivity and costs on supply chain prices and profits

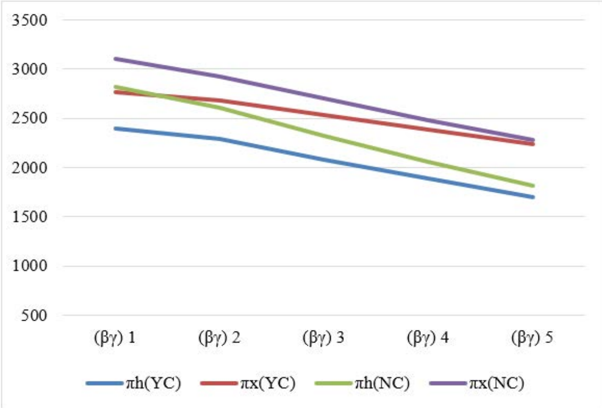

Figure 6. Comparison of supply chain profits with and without blockchain technology

4.3 SC Model

4.3.1 Calculation results

Hong Kong Free Trade Port:

$\frac{\partial Px}{\partial f} = -(167\,\mathrm{b}/17)/\left((167^{*}\,\mathrm{b}^{\wedge}2)/20 - 167/10\right) > 0$

Hainan Free Trade Port:

$\frac{\partial \pi \mathrm{h}}{\partial f} = \frac{\partial\left(-\left(167*((5*\,\mathrm{b}*\mathrm{f})/17*(20*\,\mathrm{b}*\mathrm{f}))/\left(6800*\left(\mathrm{b}^{2}-2\right)\right)\right)\right)}{\partial f} > 0$

$\frac{\partial Ph}{\partial f} = \left(-80 + 20\,\mathrm{b}^{\wedge}2\right)/\left(68^{*}\left(\mathrm{b}^{\wedge}2 - 2\right)\right)$, in certain ranges, b makes $\frac{\partial Ph}{\partial f} < 0$, and in others, $\frac{\partial \pi \mathrm{h}}{\partial f} > 0$.

4.3.2 Result analysis

The analysis utilizes numerical values inserted into the model to sequentially assess the impact of consumer sensitivity on the supply chain's sales prices and profits. With $\mathrm{a} = 100,\ \mathrm{b} = 0.5, \mathrm{w} = 20, \mathrm{e} = 0.5,\ \mathrm{T_h} = 1, \mathrm{t_x} = 2,\ \mathrm{A_h} = \beta^{*}\ \mathrm{T_h};\quad \mathrm{Ax} = \beta^{*}\mathrm{t_x} - \gamma^{*}(1-\mathrm{e})$, the effects of increased verification costs associated with the use of blockchain technology are shown in Figure 7.

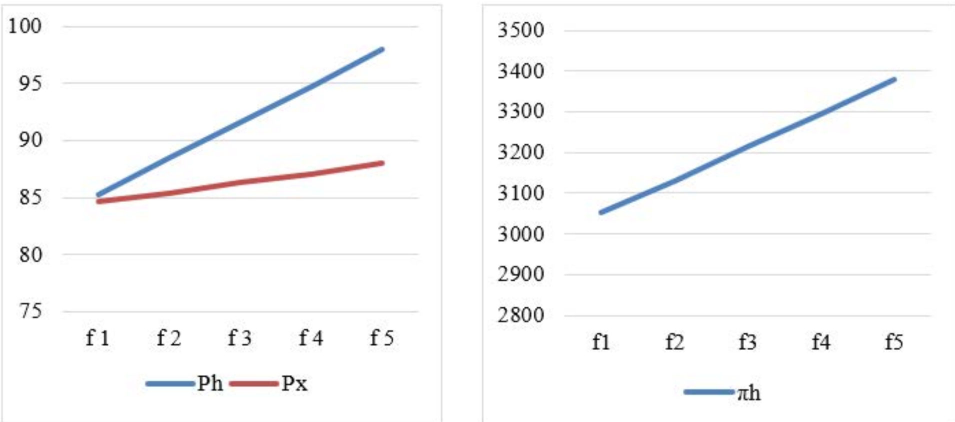

Figure 7. Impact of increased verification costs on supply chain prices and profits

When the verification cost (denoted as f) is fixed and only the consumer sensitivity to the time taken for clearance inspection increases, the comparison between scenarios where only Hainan Free Trade Port adopts blockchain technology and scenarios where it does not, in terms of sales prices and supply chain profits, is illustrated in Figure 8.

Sales Price Trends: When only Hainan Free Trade Port employs blockchain technology, the sales price of the Hong Kong Free Trade Port increases with the rise in the unit verification costs of Hainan's blockchain technology. In contrast, the supply chain profit of Hainan Free Trade Port increases with rising verification costs. The sales price is influenced by the price elasticity coefficient, with certain elasticity coefficients causing the sales price to decrease as verification costs increase.

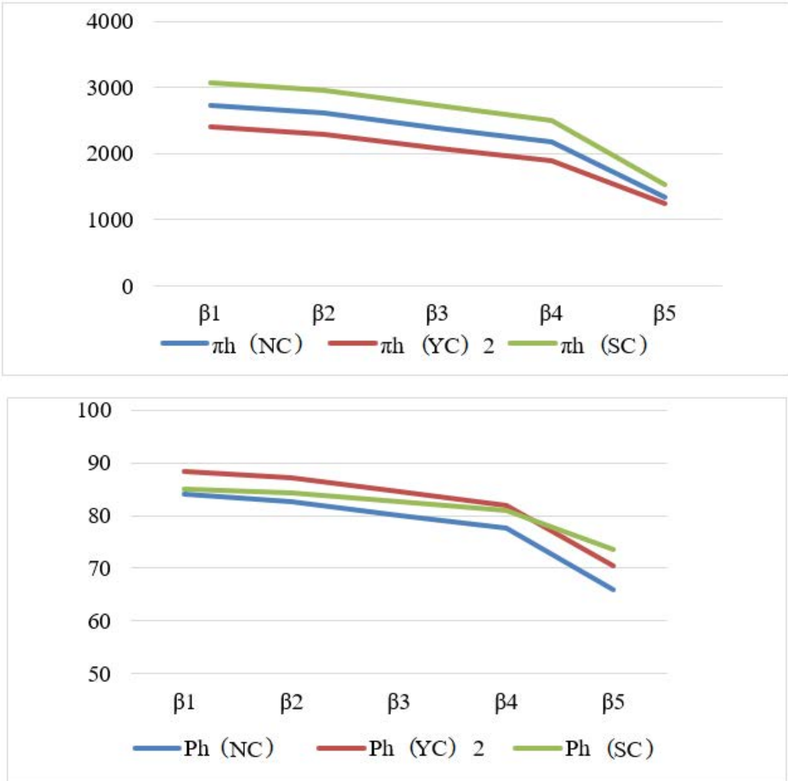

Figure 8. Impact of increased time sensitivity on Hainan's sales prices and supply chain profits under different models

Impact of Time Sensitivity: Considering only the factor of time sensitivity, there exists a threshold for time sensitivity. Below this threshold, profits from using blockchain technology exclusively at Hainan Free Trade Port are higher than the other two models. However, when this threshold is exceeded, both ports employing blockchain technology yield profits superior to the other models.

5 Conclusion and Summary

5.1 Conclusion

(1) Regardless of Blockchain Technology Usage:

Retail Prices: Retail prices decrease as consumer sensitivity to clearance time and product authenticity increases. With growing sensitivity, the price gap between the ports under the same model narrows, eventually converging at a certain sensitivity threshold.

Supply Chain Profits: Profits for both Hong Kong and Hainan Free Trade Ports' supply chains decrease with increasing consumer sensitivity, but the decline is more gradual for Hong Kong, resulting in a widening profit gap due to sensitivity.

(2) When Both Ports Use Blockchain Technology:

A threshold exists for consumer sensitivity; below this, profits using blockchain are lower than without it, albeit with a more stable decrease. Beyond this threshold, blockchain-enabled supply chain profits surpass those without blockchain.

With blockchain, product sales prices increase with rising unit verification costs, and certain price elasticity coefficients lead to profit increases with higher inspection costs.

(3) When Only Hainan Uses Blockchain Technology:

Sales prices and supply chain profits for both ports increase with the rise in Hainan's blockchain verification costs. Sales prices are also influenced by price elasticity, with a range where prices decrease as verification costs increase.

(4) Comparison of the Three Models:

Considering only time sensitivity, both blockchain-using models have higher sales prices than the non-blockchain model. A threshold exists for time sensitivity; below it, the solo blockchain model yields higher profits, while above it, the dual blockchain model outperforms the others.

5.2 Implications and Recommendations

(1) Supply Chain Construction: For products with sensitive consumer groups, lower sales prices or early blockchain adoption can minimize the price gap and demand reduction due to sensitivity. Accurate market research to gauge consumer sensitivity is crucial for choosing the most profitable channels.

(2) Blockchain Technology Advantages: Despite higher sales prices with rising verification costs, blockchain technology still holds a significant advantage in profit, especially in diverse consumer markets due to its greater elasticity.

(3) High-Value Industries: For high-tech and luxury industries, early blockchain adoption can establish profit advantages as higher verification costs imply more valuable products.

(4) Price Control in Supply Chain: Pricing should be within a reasonable range compared to similar products to leverage blockchain technology for profit maximization.

5.3 Model Limitations

Inadequate Factors: The model overlooks many demand-influencing factors, such as transportation time from different ports and detailed tax deductions.

Calculation and Data Analysis: Due to complexities, exact numerical ranges weren't derived, and the analysis relied heavily on derivatives, leading to weaker argumentative support. Future studies should focus on stronger model construction, calculation, and proof capabilities, using larger data sets for big data analysis.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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