

Adopting Blockchain in Fresh Supply Chains: Low or High Level?

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Abstract

This study addresses the significant challenge posed by information asymmetry in the fresh supply chain, which severely impacts consumers' online shopping experience and presents major challenges for online fresh retailers and suppliers. Leveraging the authenticity and traceability of blockchain technology, we propose an innovative solution that introduces blockchain to help consumers access product quality information. The study analyzes how two competing retailers (an incumbent and a new entrant) adopt varying degrees of blockchain strategies based on different market resources to validate the technology's value in the fresh supply chain. The findings suggest that, in certain cases, when the incumbent retailer adopts blockchain to a high degree, both parties can achieve a win-win outcome, generating a blockchain spillover effect influenced by channel competition. Interestingly, the impact of information asymmetry on retailer profits follows a non-linear trend, where increased information asymmetry can optimize profits under competitive conditions. Suppliers and incumbents must balance operational costs and blockchain benefits to decide on the degree of adoption. New entrants can leverage the incumbent's blockchain spillover effect or participate in a consortium blockchain to share costs, enabling them to benefit from blockchain technology and achieve win-win outcomes across supply chain members. This study provides guidance for fresh supply chain participants, encouraging them to explore collaborative blockchain models, reduce costs through strategic alliances, and enhance supply chain efficiency for mutual benefit.

Keywords

Fresh Supply Chain, Information Asymmetry, Blockchain Technology, Retailer Competition, Cost-Sharing

1. Introduction

With the rapid growth of e-commerce, online sales of fresh products have become a crucial part of the global supply chain. According to a report by eMarketer, global e-commerce sales reached nearly \$6 trillion in 2023 and are expected to grow to \$7 trillion by 2025, almost double the amount in 2019 (Insider Intelligence, 2023). This growth demonstrates the vast potential of the online retail market. However, the fresh e-commerce sector faces significant challenges, with one of the most pressing issues being information asymmetry (Wang & Li, 2012; Xiong & Xiong, 2019). In online fresh supply chains, consumers are unable to directly access the true quality of products, leading to a discount in their valuation of product quality. This information asymmetry not only reduces consumer trust but can also lead to market failures, affecting the overall efficiency of the supply chain. For example, in 2018, the well-known Chinese retailer Hema Fresh was exposed for selling expired food, severely damaging consumer trust in fresh e-commerce. Similarly, in the same year, a U.S. outbreak of E. coli linked to romaine lettuce caused multiple illnesses and deaths. The lack of transparency in the supply chain made it difficult to trace the source of contamination, increasing consumer concerns about the safety of fresh products. These cases highlight the negative impact of information asymmetry on the fresh supply chain.

To address this issue, blockchain technology has emerged as an innovative solution. Known for its decentralized, immutable, and traceable characteristics, blockchain enables transparency and information sharing across all stages of the supply chain (Kshetri, 2018; Zhang & Shi, 2018). Compared to traditional tracking technologies like the Internet of Things (IoT), barcodes, QR codes, and RFID, blockchain provides higher transparency and credibility, reducing the risk of data manipulation (Francisco & Swanson, 2018). Specifically, blockchain offers the following advantages in the fresh supply chain: 1) Enhancing transparency: Blockchain allows all supply chain participants to share real-time information on product production, transportation, and sales. For example, Walmart's food traceability system, developed in collaboration with IBM, reduced the traceability time of mangoes from 7 days to 2.2 seconds, greatly improving supply chain transparency and efficiency (IBM, 2017). 2) Building consumer trust: The immutability of blockchain ensures the authenticity of information, helping consumers better understand product quality and enhancing their trust. JD Fresh uses blockchain to make information from suppliers, logistics, and warehousing transparent, allowing consumers to view detailed traceability information by scanning a QR code. 3) Reducing operational costs: While the initial investment in blockchain technology is significant, it can reduce the costs of manual verification and dispute resolution in the long run (Deloitte, 2018).

However, the degree of blockchain adoption varies among different online retailers. Incumbent retailers (such as JD Fresh and Walmart), with abundant market resources and decision-making power, can choose to implement blockchain technology extensively, disclosing real quality information during the sales period

and requiring suppliers to upload information on the blockchain, enabling full traceability. For example, Walmart has been collaborating with IBM since 2016 to track food supply chains using blockchain, successfully reducing the traceability time for products like pork from several days to a few seconds (IBM, 2017). While this strategy significantly improves consumer valuation of products, it also incurs additional operational costs, which must be shared with suppliers (Chang et al., 2019). According to The Wall Street Journal, Walmart requires suppliers to use its designated blockchain system, increasing suppliers' technological investments. New entrants (such as Dingdong Maicai and Missfresh), with limited resources, tend to adopt blockchain technology to a lesser degree, mainly sharing product quality information during the sales period without requiring suppliers to disclose further quality data. For instance, while Dingdong Maicai began experimenting with blockchain traceability in 2020, it has focused primarily on high-end products with limited information disclosure. Missfresh, on the other hand, relies more on its internal quality control system and has not yet implemented blockchain technology on a large scale.

These varying degrees of blockchain adoption have intensified competition among online fresh platforms. According to iResearch Consulting Group, the number of users in China's fresh e-commerce sector reached 350 million in 2022, but the market concentration remained low, with the top 10 companies holding only about 50% of the market share (iResearch Consulting Group, 2023). At the same time, consumer concerns about food safety and quality continue to rise. According to a Nielsen survey, over 70% of Chinese consumers are willing to pay a premium for traceable fresh products, making blockchain technology a critical tool for gaining a competitive edge (NielsenIQ, 2021). In the fierce market competition, how to use blockchain technology to optimize supply chain performance and enhance competitive advantage has become an urgent research topic.

Furthermore, traditional retail giants are actively exploring blockchain technology to gain a market advantage. For example, Carrefour launched a blockchain-based food traceability project in Europe, covering products such as chicken and milk. After its implementation, sales of the related products increased by more than 20%. This has further intensified the competitive pressure on online fresh platforms. Meanwhile, small and medium-sized fresh e-commerce companies, limited by resources and technology, face challenges in adopting blockchain (Saberi et al., 2019). They lack the ability to make large-scale investments or secure full cooperation from suppliers (Wang et al., 2019). In this situation, small businesses may need to seek partnerships or form alliances to jointly promote the use of blockchain technology and avoid falling behind in the competition.

In conclusion, the disparity in blockchain adoption is reshaping the competitive landscape of fresh e-commerce. Large incumbents leverage their resource advantages to deeply implement blockchain, improving supply chain transparency and consumer trust, thus occupying a dominant market position. New entrants and small businesses need to find innovative strategies to use blockchain within

limited resources to meet consumer expectations for product quality and safety. Therefore, studying how to effectively apply blockchain under different resource conditions to optimize supply chain performance and enhance competitiveness has important theoretical and practical significance. This paper develops a competitive model of a fresh supply chain involving suppliers, incumbent online retailers, and new entrant online retailers. By analyzing the impact of varying degrees of blockchain adoption on the decisions and profits of supply chain members, it explores how retailers can effectively apply blockchain technology under resource constraints to meet consumer demand and enhance their market competitiveness. It also examines the trade-off between blockchain effects and costs, analyzing the value of blockchain in the fresh supply chain.

Specifically, this study focuses on the following aspects:

1) Impact of information asymmetry on the supply chain: An in-depth analysis of how information asymmetry affects the decisions, pricing, and profits of suppliers and retailers in the fresh supply chain, revealing the market failures and inefficiencies caused by information asymmetry.

2) Comparison of blockchain adoption strategies: An exploration of how different levels of blockchain adoption (high, low, or none) affect the profits and market competitiveness of supply chain participants, analyzing their optimal strategy choices under various market conditions.

3) Supply chain game and strategy optimization: A two-stage Stackelberg game model is constructed to study the strategic interactions between retailers in a competitive environment, considering the willingness of suppliers to cooperate and the cost-sharing mechanisms.

4) Managerial insights and strategic recommendations: Based on the model analysis, this study provides specific recommendations on the blockchain adoption strategies that retailers and suppliers should take under different resource conditions to optimize supply chain performance and enhance competitiveness.

Through this research, the paper aims to provide theoretical support and practical guidance for the application of blockchain technology in the fresh supply chain. It helps incumbent and new entrant online retailers develop effective blockchain adoption strategies under different resource conditions, improve supply chain transparency and efficiency, meet consumer expectations for product quality and safety, and achieve win-win outcomes for all supply chain members.

The remainder of this paper is structured as follows: Section 2 reviews the literature. Section 3 introduces the problem and establishes the model. Section 4 provides a benchmark where both R_1 and R_2 adopt blockchain technology and analyzes their equilibrium solutions. Section 5 analyzes the equilibrium prices and profits under different blockchain adoption models. Section 6 compares the different models and provides the optimal strategies for supply chain members. Section 7 presents the conclusions, managerial implications, research limitations, and future research directions.

2. Literature Review

This study involves two streams of literature: the impact of blockchain technology on fresh food supply chains and retailer competition.

2.1. The Impact of Blockchain Technology on Fresh Food Supply Chains

The first stream of literature focuses on the impact of blockchain technology on fresh food supply chains. [Saber et al. \(2019\)](#) explored how blockchain technology promotes sustainable supply chain management, emphasizing its role in enhancing supply chain transparency and traceability. [Kshetri \(2018\)](#) pointed out that blockchain can improve information transparency and reduce transaction costs, thereby achieving supply chain management objectives. These studies demonstrate the potential of blockchain in improving information sharing and trust mechanisms within supply chains. In the food supply chain sector, [Tian \(2017\)](#) proposed a food traceability system based on HACCP, blockchain, and the Internet of Things (IoT), highlighting the importance of blockchain in food safety. [Chen et al. \(2020\)](#) conducted a thematic analysis of the adoption process, benefits, and challenges of blockchain technology in food supply chains. [Kamble et al. \(2020\)](#) developed a blockchain-enabled traceability model for agricultural supply chains, examining its impact on supply chain performance. Several studies also analyzed consumer awareness of traceability. [Fan et al. \(2022\)](#) considered the cost of using blockchain technology and consumer awareness of traceability, exploring whether the supply chain should adopt blockchain technology and discussing the coordination issues related to its adoption. [Pun et al. \(2021\)](#) analyzed the use of blockchain-based quality traceability to convey quality information in the context of consumer concerns about privacy. They found that blockchain is more effective than pricing strategies in reducing post-purchase regret and enhancing social welfare.

While the above studies deeply explore the application value of blockchain technology in supply chains, they primarily focus on the overall optimization of supply chains at a macro level, lacking analysis of the competitive relationships between supply chain members within specific market structures. Addressing this research gap, the innovations of this study are: 1) Focus on the competitive structure of the fresh food supply chain: This study builds a game model involving a supplier, an incumbent online retailer, and a new entrant online retailer, deeply analyzing the decision-making and interactions of each party under information asymmetry. 2) Consideration of varying degrees of blockchain application: This study explores the strategies of retailers with different resource conditions in choosing high or low levels of blockchain application and examines their impact on supply chain performance. 3) Introduction of consumer sensitivity to product quality: The study analyzes how consumer sensitivity to product quality information asymmetry affects the profits and strategic choices of supply chain members.

2.2. Retailer Competition

The second stream of literature relevant to this study focuses on retailer competition. Various studies have explored the effects of retailer competition on business operations and management strategies. Ha et al. (2022) developed a game theory model to study the encroachment and information-sharing decisions in supply chains selling through online retail platforms, analyzing the relationship between the degree of inter-channel competition and information sharing. Li et al. (2016) considered a dual-channel supply chain composed of risk-neutral suppliers and risk-averse retailers, analyzing the impact of uncertain competition in the market. Du et al. (2022) developed a game theory model to study the competitive effects of personalized pricing in the presence of dominant retailers, marginal retailers, and common suppliers. Akturk & Ketzenberg (2022) analyzed the impact of offline store information disclosure on online channel demand. Wang et al. (2022) applied game theory models to study blockchain adoption strategies among competing retailers. Zhu et al. (2023) analyzed the impact of blockchain on product information sharing among supply chain members.

The above literature primarily focuses on retailer competition strategies, channel coordination, and the effects of price and demand uncertainty on supply chains. However, these studies often assume that retailers have equal resources and market positions, with limited exploration of how the introduction of blockchain technology impacts the competitive landscape. The innovations of this study are: 1) Introduction of asymmetric retailer competition structures: Unlike traditional symmetric competition models, this study considers competition between incumbent online retailers and new entrant online retailers, reflecting the differences in resources and market influence in the real world. 2) Integration of blockchain technology application levels: This study incorporates varying levels of blockchain technology application into retailer competition strategies, analyzing the impact of technology introduction on retailer pricing, market share, and profitability. 3) Consideration of information asymmetry and consumer behavior: This study introduces consumer sensitivity to product quality information asymmetry, exploring how information asymmetry affects competition between retailers and the overall performance of the supply chain.

2.3. Research Contributions

Through the above literature review, it is evident that existing studies have deeply explored the application of blockchain technology and retailer competition, but few have combined the two, especially in the context of fresh food supply chains. The innovation of this study lies in constructing a game model involving a supplier, an incumbent online retailer, and a new entrant online retailer. It focuses on analyzing how competing retailers with different social resources decide the degree of blockchain technology application in an environment of information asymmetry. Additionally, the study examines the value of blockchain effects in fresh food supply chains and the potential for win-win cooperation through

consortium blockchains, providing new theoretical support and strategic recommendations for the management practices of fresh food supply chains.

3. Model Description

3.1. Problem Description

In a fresh supply chain, we consider a competitive structure comprising a supplier (S), an incumbent online retailer (R1), and a new entrant online retailer (R2). Due to the consumers' inability to directly obtain the true quality information of products, they apply a quality discount during purchasing, and this valuation is influenced by their sensitivity to quality (Zhang et al., 2023). Retailers can introduce blockchain technology to disclose the true quality of products, reducing the negative effects of information asymmetry and thus enhancing consumer trust (Kshetri et al., 2018). Blockchain technology allows consumers to more accurately understand product quality, thereby affecting the market competitiveness of retailers.

In this supply chain, both retailers' source fresh products from the same supplier for sale. The incumbent retailer holds more market resources and decision-making power, while the new entrant lacks sufficient capital and market influence. Specifically, the interaction between the supplier and retailers can be divided into the following two aspects:

1) Incumbent retailer's decision: The incumbent retailer can choose to introduce a high level of blockchain technology (H), not only disclosing the true quality information during the sales period but also requiring the supplier to upload data onto the blockchain for full traceability, enhancing consumers' valuation of the products. For example, JD Fresh utilizes blockchain technology to upload information regarding the supplier, logistics, and warehousing, achieving full traceability from the origin to the consumer. Consumers can scan a QR code on the product to view detailed traceability information, which boosts their recognition of product quality. However, this incurs additional operational costs, which are shared between the platform and the supplier (Saber et al., 2019). The incumbent retailer may also opt for a low level of blockchain technology (L), only paying the fixed costs for the equipment to share product quality information during the sales period. Alternatively, they can maintain their current operating model (N), avoiding additional costs. However, based on our comparison with benchmarks, we find that under certain equipment costs, the incumbent retailer is motivated to adopt blockchain technology. Therefore, we mainly analyze the decision-making of the incumbent retailer after introducing a low level of blockchain technology.

2) New entrant retailer's decision: With limited resources, the new entrant retailer can only choose to adopt a low level of blockchain technology (L) or maintain the current model (N), lacking the ability to require the supplier to participate in quality information disclosure. Information such as the place of origin, supplier name, and production date helps consumers understand the product's source and freshness. For example, as an emerging fresh e-commerce platform, Dingdong

Maicai is gradually introducing quality information-sharing mechanisms into its supply chain. However, as the collaboration depth between Dingdong Maicai and its suppliers is still being developed, full information sharing throughout the supply chain has not yet been realized. For instance, detailed data such as cultivation or breeding processes, temperature control during transportation, and quality inspection reports may not be fully disclosed.

Based on the different decisions of the incumbent and new entrant retailers, the following four sub-models can be constructed: R1 adopting low blockchain technology (LN), R1 adopting high blockchain technology (HN), both retailers adopting low blockchain technology (LL), and R1 adopting high blockchain technology while R2 adopts low blockchain technology (HL), as shown in **Figure 1**.

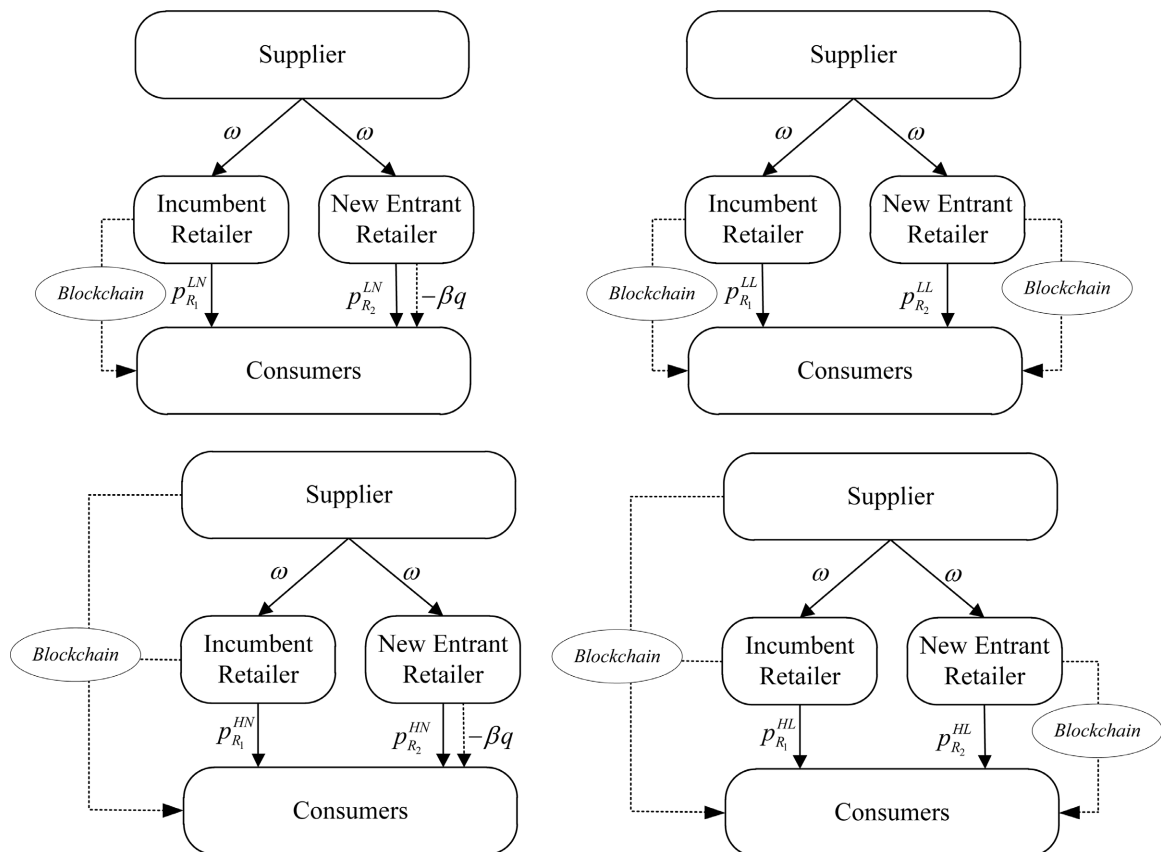


Figure 1. Model.

3.2. Assumptions

The following assumptions are made in the subsequent analysis:

- **Assumption 1:** Blockchain costs. Referring to literature (Chang et al., 2019), blockchain can reduce manual identification costs. Therefore, when a low level of blockchain technology is applied, the model considers only the fixed cost F , excluding operational costs. In the case of a high level of blockchain adoption by the incumbent retailer, referring to Liu et al. (2022), the operational cost $2c$ will be shared between the supplier and the incumbent retailer.

- Assumption 2:** Blockchain technology. As shown in **Table 1**, when blockchain technology is not adopted in the market, consumers' valuation of products is reduced due to information asymmetry in the online market, resulting in a quality discount (βq), where q represents consumers' uncertainty about product quality, and β indicates their sensitivity (Zhang et al., 2023). After the adoption of blockchain technology, information asymmetry will be effectively mitigated. In the case of high blockchain adoption, the incumbent retailer will benefit from the enhancement effect (B) brought by blockchain, further expanding R_1 's market.
- Assumption 3:** According to (Shang et al., 2016), the demand function is assumed to be $D_i = 1 - p_i + \gamma p_j$, where γ represents the level of competition between channels.
- Assumption 4:** To generalize the analysis, we assume the production cost is zero, and there are no leftover products or additional costs.

Table 1. Consumer demand.

	R₁ (H)	R₁ (L)	R₂ (N)
R₂ (L)	$D_{R_1}^{HL} = 1 - p_{R_1} + \gamma p_{R_2} + B$ $D_{R_2}^{HL} = 1 - p_{R_1} + \gamma p_{R_2}$	$D_{R_1}^{LL} = 1 - p_{R_1} + \gamma p_{R_2}$ $D_{R_2}^{LL} = 1 - p_{R_1} + \gamma p_{R_2}$	/
R₂ (N)	$D_{R_1}^{HN} = 1 - p_{R_1} + \gamma p_{R_2} + B$ $D_{R_2}^{HN} = 1 - p_{R_2} + \gamma p_{R_1} - \beta q$	$D_{R_1}^{LN} = 1 - p_{R_1} + \gamma p_{R_2}$ $D_{R_2}^{LN} = 1 - p_{R_1} + \gamma p_{R_2} + B$	$D_{R_1}^{LL} = 1 - p_{R_1} + \gamma p_{R_2} - \beta q$ $D_{R_2}^{LL} = 1 - p_{R_1} + \gamma p_{R_2} - \beta q$

3.3. Decision Sequence

As shown in **Figure 2**, the retailers and suppliers follow a two-stage Stackelberg game: in the T0 stage, R_1 decides whether to adopt blockchain technology at a high or low level; in the T1 stage, R_2 decides whether to adopt blockchain technology at a low level. Then S , R_1 , and R_2 make pricing decisions: S decides on the wholesale price in the T2 stage, R_1 then determines the retail price based on S 's wholesale price in the T3 stage. Finally, R_2 sets its own retail price in the T4 stage based on the wholesale price and R_1 's pricing decision.

The main parameter definitions in this paper are shown in **Table 2**:

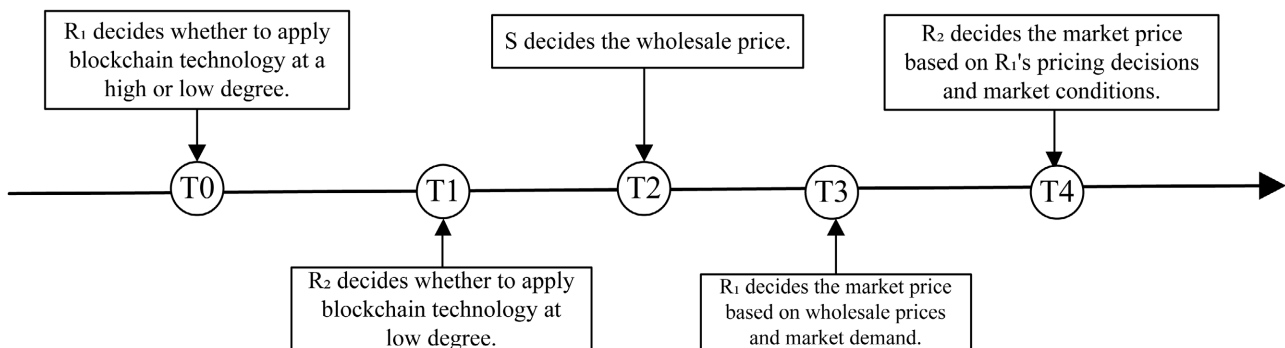


Figure 2. Decision sequence.

Table 2. Parameter definitions.

Notations	Descriptions
<i>Decision variables</i>	
ω	The supplier's wholesale price
p_{R_1}	The incumbent retailer's unit retail price
p_{R_2}	The new entrant retailer's unit retail price
<i>Parameters</i>	
q	Degree of information asymmetry
β	Consumers' sensitivity to information asymmetry
γ	Degree of channel substitution
F	Fixed cost of blockchain deployment
c	Operational cost under model H
B	Blockchain enhancement effect
D	The demand
π	The profit
<i>Superscripts</i>	
$XY (X = \{N, L, H\}, Y = \{N, L\})$	Five models (NN, LN, HN, LL, HL)
<i>Subscripts</i>	
$R_1/R_2/S$	The retailers R_1 and R_2 ; The supplier S

4. Benchmark

Before analyzing the blockchain application strategies of R_1 and R_2 , we examined the market scenario where blockchain technology is not introduced. Equations (1)-(3) represent the profit expressions for the supplier S , R_1 , and R_2 , respectively. Using backward induction, we derived Lemma 1. The calculation process is shown in the Appendix.

$$\pi_S^{NN} = \omega(1 - p_{R_1} + \gamma p_{R_2} - \beta q) + \omega(1 - p_{R_2} + \gamma p_{R_1} - \beta q) \quad (1)$$

$$\pi_{R_1}^{NN} = p_{R_1}(1 - p_{R_1} + \gamma p_{R_2} - \beta q) \quad (2)$$

$$\pi_{R_2}^{NN} = p_{R_2}(1 - p_{R_2} + \gamma p_{R_1} - \beta q) \quad (3)$$

Lemma 1. The equilibrium results for the NN strategy are as follows:

$$\omega^{NN} = \frac{1 - q\beta}{2 - 2\gamma}; \quad p_{R_1}^{NN} = \frac{(-1 + q\beta)(-6 + \gamma + 3\gamma^2)}{4(-1 + \gamma)(-2 + \gamma^2)}; \quad p_{R_2}^{NN} = -\frac{(-1 + q\beta)(12 - 2\gamma - 7\gamma^2 + \gamma^3)}{8(-1 + \gamma)(-2 + \gamma^2)};$$

$$D_{R_1}^{NN} = \frac{1}{8}(1 - q\beta)(2 + \gamma); \quad D_{R_2}^{NN} = -\frac{(-1 + q\beta)(-4 - 2\gamma + \gamma^2)}{8(-2 + \gamma^2)};$$

$$\pi_{R_1}^{NN} = -\frac{(-1+q\beta)^2(2+\gamma)^2}{32(-2+\gamma^2)}; \quad \pi_{R_2}^{NN} = \frac{(-1+q\beta)^2(-4-2\gamma+\gamma^2)^2}{64(-2+\gamma^2)^2};$$

$$\pi_S^{NN} = -\frac{(-1+q\beta)^2(-8-4\gamma+3\gamma^2+\gamma^3)}{16(-1+\gamma)(-2+\gamma^2)}.$$

Theorem 1. Through sensitivity analysis of all equilibrium results in Lemma 1 regarding the parameters β , γ , and q , we obtain the following conclusions: the supplier S, R_1 , and R_2 are negatively correlated with β and q , while positively correlated with γ .

Proof: The proof process is complex, and the specific details are shown in the Appendix.

Theorem 1 indirectly verifies the profound impact of uncertainty regarding consumers' perception of the quality of online fresh products. This uncertainty directly leads to a decline in the overall operational efficiency of the supply chain, affecting both the profits of suppliers and retailers as well as their market competitiveness. Since consumers cannot accurately assess the true quality of the products, they tend to lower their trust in them, resulting in reduced demand. This creates a ripple effect across the supply chain, weakening the overall market performance. Additionally, Theorem 1 further reveals that in scenarios with a high degree of channel substitution, all members of the supply chain can improve their performance by adapting their strategies to the competitive environment.

The sensitivity analysis in the following sections will be based on Theorem 1.

5. Equilibrium Analysis

5.1. R_1 Adopts Low-Level Blockchain Technology (LN)

When only R_1 chooses to adopt low-level blockchain technology, the incumbent retailer is no longer affected by information asymmetry and is required to pay the fixed cost of blockchain technology. Meanwhile, R_2 chooses to maintain the status quo. By solving Equations (4)-(6) through backward induction, Lemma 2 is derived. The calculation process is shown in the Appendix.

$$\pi_S^{LN} = \omega(1-p_{R_1} + \gamma p_{R_2}) + \omega(1-p_{R_2} + \gamma p_{R_1} - \beta q) \quad (4)$$

$$\pi_{R_1}^{LN} = p_{R_1}(1-p_{R_1} + \gamma p_{R_2}) \quad (5)$$

$$\pi_{R_2}^{LN} = p_{R_2}(1-p_{R_2} + \gamma p_{R_1} - \beta q) \quad (6)$$

Lemma 2. The equilibrium results for the LN strategy are as follows:

$$\omega^{LN*} = \frac{8+4\gamma-3\gamma^2-\gamma^3+q\beta(-4-2\gamma+\gamma^2+\gamma^3)}{2(-1+\gamma)(-8-4\gamma+3\gamma^2+\gamma^3)};$$

$$p_{R_1}^{LN*} = \frac{-48-16\gamma+46\gamma^2+15\gamma^3-10\gamma^4-3\gamma^5+q\beta(8+24\gamma-12\gamma^2-19\gamma^3+4\gamma^4+3\gamma^5)}{4(-1+\gamma)(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)};$$

$$\begin{aligned}
 p_{R_1}^{LN*} &= \frac{-96 - 32\gamma + 100\gamma^2 + 26\gamma^3 - 27\gamma^4 - 4\gamma^5 + \gamma^6 - q\beta(-80 + 16\gamma + 76\gamma^2 - 12\gamma^3 - 19\gamma^4 + 2\gamma^5 + \gamma^6)}{8(-1 + \gamma)(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\
 D_{R_1}^{LN*} &= \frac{-16 - 16\gamma + 2\gamma^2 + 5\gamma^3 + \gamma^4 - q\beta(8 - 8\gamma - 8\gamma^2 + 3\gamma^3 + \gamma^4)}{8(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\
 D_{R_2}^{LN*} &= \frac{32 + 32\gamma - 12\gamma^2 - 14\gamma^3 + \gamma^4 + \gamma^5 - q\beta(48 + 16\gamma - 36\gamma^2 - 8\gamma^3 + 7\gamma^4 + \gamma^5)}{8(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\
 \pi_{R_1}^{LN*} &= \frac{-\left(-16 - 16\gamma + 2\gamma^2 + 5\gamma^3 + \gamma^4 - q\beta(8 - 8\gamma - 8\gamma^2 + 3\gamma^3 + \gamma^4)\right)^2}{32(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)^2} - F; \\
 \pi_{R_2}^{LN*} &= \frac{\left(32 + 32\gamma - 12\gamma^2 - 14\gamma^3 + \gamma^4 + \gamma^5 - q\beta(48 + 16\gamma - 36\gamma^2 - 8\gamma^3 + 7\gamma^4 + \gamma^5)\right)^2}{64(-2 + \gamma^2)^2(-8 - 4\gamma + 3\gamma^2 + \gamma^3)^2}; \\
 \pi_S^{LN*} &= -\frac{\left(8 + 4\gamma - 3\gamma^2 - \gamma^3 + q\beta(-4 - 2\gamma + \gamma^2 + \gamma^3)\right)^2}{16(-1 + \gamma)(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}.
 \end{aligned}$$

Theorem 2. Through sensitivity analysis of all equilibrium results in Lemma 2 regarding the parameters β , γ , and q , the following conclusions are obtained: when $0 < \gamma < \sqrt{0.681}$, R_1 's demand and profit are positively correlated with β and q . However, R_1 's demand is negatively correlated with γ only under the following conditions:

$$\left(\left(\frac{16}{27} < \beta \leq \frac{2}{3} \ \& \ \& \ \gamma_1^{LN} < \gamma < 1 \ \& \ \& \ q_1^{LN} < q < 1 \right) \parallel \left(\sqrt{0.688} < \beta < 1 \ \& \ \& \ 0 < \gamma < 1 \ \& \ \& \ q_1^{LN} < q < 1 \right) \right) \\
 \left(\frac{2}{3} < \beta \leq \sqrt{0.688} \ \& \ \& \ q_1^{LN} < q < 1 \left(\left(0 < \gamma < \gamma_1^{LN} \right) \parallel \left(\gamma_1^{LN} < \gamma < 1 \right) \right) \right)$$

R_1 and R_2 's profits are negatively correlated with γ only when $2/3 < \beta < 1$ & $0 < \gamma < \gamma_2^{LN}$ & $q_2^{LN} < q < 1$.

The rest is consistent with Theorem 1 and will not be repeated here.

Proof: The proof process is complex, and the specific details are shown in the Appendix.

Theorem 2 indicates that when R_1 adopts blockchain technology to address information asymmetry, it no longer suffers demand losses due to information asymmetry. According to Theorem 1, R_1 's demand decreases with consumers' information asymmetry. However, after adopting blockchain technology, blockchain helps consumers access information by sharing sales-period data, thereby reducing the impact of information asymmetry on R_1 's demand.

When the substitution degree between R_1 and R_2 is low, R_1 can even benefit from information asymmetry. This is because as R_2 suffers increasingly from information asymmetry, R_1 can capture a portion of R_2 's market, thereby increasing its own demand. However, when the substitution degree is high, the products offered by the two retailers become more homogeneous in the eyes of consumers,

intensifying price competition. In this case, the demand growth is insufficient to offset the losses caused by price competition, preventing R_1 from optimizing its profits.

When blockchain is not applied, the increase in the substitution degree does not directly harm R_1 . However, since R_1 is no longer affected by information asymmetry, an increase in the substitution degree will inevitably lead to a new competitive landscape. Only when information asymmetry and consumer sensitivity are sufficiently high will competition increase, resulting in a decline in R_1 's demand. This is because, at this point, the losses due to competition exceed the demand advantage gained from blockchain. Therefore, when consumer sensitivity is high, R_1 's demand is likely to suffer in any scenario. In contrast, when consumer sensitivity is low, only a high degree of channel competition will lead to an irreversible decline in R_1 's demand. Interestingly, when consumer sensitivity is moderate, increasing competition in both low and high competition environments will lead to losses. This is because low competition means a low degree of substitution, resulting in minimal demand growth. On the other hand, high competition brings excessive competition losses. Therefore, only under moderate competition can demand growth effectively balance out price competition losses.

As R_1 's price increases with the substitution degree, its profit outlook is more optimistic than its demand performance. This is because the price increase offsets part of the demand loss. As a result, R_1 's profit will only suffer when both consumer sensitivity and information asymmetry are high. Therefore, R_1 should prioritize adopting blockchain technology to reduce the demand loss caused by information asymmetry and leverage this advantage to capture the market when the substitution degree is low. Meanwhile, in environments with high substitution degrees and high information asymmetry, R_1 needs to employ flexible pricing strategies to offset the negative impact of price competition on profits.

5.2. R_1 and R_2 Both Adopt Low-Level Blockchain Technology (LL)

When both R_1 and R_2 choose to adopt low-level blockchain technology, the entire market is no longer affected by information asymmetry, and this sub-model is similar to the benchmark model. By solving Equations (7)-(9) through backward induction, Lemma 3 is derived. The calculation process is shown in the Appendix.

$$\pi_S^{HN} = (\omega - c)(1 - p_{R_1} + \gamma p_{R_2} + B) + \omega(1 - p_{R_2} + \gamma p_{R_1} - \beta q) \quad (7)$$

$$\pi_{R_1}^{HN} = (p_{R_1} - c)(1 - p_{R_1} + \gamma p_{R_2} + B) - F \quad (8)$$

$$\pi_{R_2}^{HN} = p_{R_2}(1 - p_{R_2} + \gamma p_{R_1} - \beta q) \quad (9)$$

Lemma 3. The equilibrium results of the LL strategy are as follows:

$$\omega^{LL*} = \frac{1}{2 - 2\gamma}; \quad p_{R_1}^{LL*} = -\frac{-6 + \gamma + 3\gamma^2}{4(-1 + \gamma)(-2 + \gamma^2)}; \quad p_{R_2}^{LL*} = \frac{12 - 2\gamma - 7\gamma^2 + \gamma^3}{8(-1 + \gamma)(-2 + \gamma^2)};$$

$$D_{R_1}^{LL*} = \frac{2 + \gamma}{8}; \quad D_{R_2}^{LL*} = \frac{-4 - 2\gamma + \gamma^2}{8(-2 + \gamma^2)};$$

$$\pi_{R_1}^{LL*} = -\frac{(2+\gamma)^2}{32(-2+\gamma^2)} - F; \quad \pi_{R_2}^{LL*} = \frac{(-4-2\gamma+\gamma^2)^2}{64(-2+\gamma^2)^2} - F; \quad \pi_S^{LL*} = -\frac{-8-4\gamma+3\gamma^2+\gamma^3}{16(-1+\gamma)(-2+\gamma^2)}.$$

The analysis of the equilibrium solution in Lemma 3 is consistent with Theorem 1 and will not be repeated here.

5.3. Only R₁ Adopts High-Level Blockchain Technology (HN)

When only R₁ adopts high-level blockchain technology, consumers can access traceable information provided by the blockchain, thereby increasing their trust in R₁, which realizes the blockchain effect. At the same time, both R₁ and the supplier S must bear the corresponding operational costs, making it crucial to analyze the blockchain effect and the costs it incurs. By solving Equations (10)-(12) through backward induction, Lemma 4 is derived. The calculation process is shown in the Appendix.

$$\pi_S^{HN} = (\omega - c)(1 - p_{R_1} + \gamma p_{R_2} + B) + \omega(1 - p_{R_2} + \gamma p_{R_1} - \beta q) \tag{10}$$

$$\pi_{R_1}^{HN} = (p_{R_1} - c)(1 - p_{R_1} + \gamma p_{R_2} + B) - F \tag{11}$$

$$\pi_{R_2}^{HN} = p_{R_2}(1 - p_{R_2} + \gamma p_{R_1} - \beta q) \tag{12}$$

Lemma 4. The equilibrium results of the HN strategy are as follows:

$$\begin{aligned} \omega^{HN*} &= \frac{8 + 4\gamma - 3\gamma^2 - \gamma^3 + B(4 + 2\gamma - 2\gamma^2) + q\beta(-4 - 2\gamma + \gamma^2 + \gamma^3)}{2(-1 + \gamma)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\ p_{R_1}^{HN*} &= \frac{\left(\begin{aligned} &-48 + 8q\beta - 16\gamma + 24q\beta\gamma + 46\gamma^2 - 12q\beta\gamma^2 + 15\gamma^3 - 19q\beta\gamma^3 - 10\gamma^4 + 4q\beta\gamma^4 - 3\gamma^5 + 3q\beta\gamma^5 \\ &+ B(-40 + 8\gamma + 34\gamma^2 - 4\gamma^3 - 6\gamma^4) + 2c(-16 + 8\gamma + 22\gamma^2 - 8\gamma^3 - 9\gamma^4 + 2\gamma^5 + \gamma^6) \end{aligned} \right)}{4(-1 + \gamma)(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\ p_{R_2}^{HN*} &= \frac{\left(\begin{aligned} &(-8 - 4\gamma + 3\gamma^2 + \gamma^3)(12 + (-2 + 4c)\gamma - (7 + 4c)\gamma^2 + (1 - 2c)\gamma^3 + 2c\gamma^4) \\ &- 2B(8 + 24\gamma - 12\gamma^2 - 19\gamma^3 + 4\gamma^4 + 3\gamma^5) - q\beta(-80 + 16\gamma + 76\gamma^2 - 12\gamma^3 - 19\gamma^4 + 2\gamma^5 + \gamma^6) \end{aligned} \right)}{8(-1 + \gamma)(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\ D_{R_1}^{HN*} &= \frac{\left(\begin{aligned} &-16 - 8q\beta - 16\gamma + 8q\beta\gamma + 2\gamma^2 + 8q\beta\gamma^2 + 5\gamma^3 - 3q\beta\gamma^3 + \gamma^4 - q\beta\gamma^4 \\ &+ 2B(-12 - 4\gamma + 5\gamma^2 + \gamma^3) + 2c(16 + 8\gamma - 14\gamma^2 - 6\gamma^3 + 3\gamma^4 + \gamma^5) \end{aligned} \right)}{8(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\ D_{R_2}^{HN*} &= \frac{\left(\begin{aligned} &(-8 - 4\gamma + 3\gamma^2 + \gamma^3)(-4 - 2\gamma - 4c\gamma + \gamma^2 + 2c\gamma^3) \\ &- 2B(8 - 8\gamma - 12\gamma^2 + 3\gamma^3 + 3\gamma^4) - q\beta(48 + 16\gamma - 36\gamma^2 - 8\gamma^3 + 7\gamma^4 + \gamma^5) \end{aligned} \right)}{8(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)}; \\ \pi_{R_1}^{HN*} &= \frac{\left(\begin{aligned} &-16 - 8q\beta - 16\gamma + 8q\beta\gamma + 2\gamma^2 + 8q\beta\gamma^2 + 5\gamma^3 - 3q\beta\gamma^3 + \gamma^4 - q\beta\gamma^4 \\ &+ 2B(-12 - 4\gamma + 5\gamma^2 + \gamma^3) + 2c(16 + 8\gamma - 14\gamma^2 - 6\gamma^3 + 3\gamma^4 + \gamma^5) \end{aligned} \right)^2}{32(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)^2} - F; \end{aligned}$$

$$\pi_{R_2}^{HN*} = \frac{\left(\begin{aligned} & -(-8-4\gamma+3\gamma^2+\gamma^3)(-4-2\gamma-4c\gamma+\gamma^2+2c\gamma^3) \\ & +2B(8-8\gamma-12\gamma^2+3\gamma^3+3\gamma^4)+q\beta(48+16\gamma-36\gamma^2-8\gamma^3+7\gamma^4+\gamma^5) \end{aligned} \right)^2}{64(-2+\gamma^2)^2(-8-4\gamma+3\gamma^2+\gamma^3)^2};$$

$$\pi_S^{HN*} = -\frac{4B^2(2+\gamma-\gamma^2)^2+4c^2(-2+\gamma^2)^2(8-4\gamma-7\gamma^2+2\gamma^3+\gamma^4)+8Bc(-16+8\gamma+22\gamma^2-8\gamma^3-9\gamma^4+2\gamma^5+\gamma^6)-4c(-2+(-1+q\beta)\gamma)(-16+8\gamma+22\gamma^2-8\gamma^3-9\gamma^4+2\gamma^5+\gamma^6)-4B(-2-\gamma+\gamma^2)(8+4\gamma-3\gamma^2-\gamma^3+q\beta(-4-2\gamma+\gamma^2+\gamma^3))+\left(8+4\gamma-3\gamma^2-\gamma^3+q\beta(-4-2\gamma+\gamma^2+\gamma^3)\right)^2}{(16(-1+\gamma)(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3))}.$$

Theorem 3. Through sensitivity analysis of all equilibrium results in Lemma 2 with respect to the parameters β , γ , q and B , the following conclusions are obtained:

When $\sqrt{0.595} < \gamma < 1$, R_2 's demand is positively correlated with B . In any situation, R_1 's demand is positively correlated with B . When $0 < \gamma < \sqrt{0.681}$, R_1 's demand is positively correlated with β and q .

For further analysis, please refer to **Figures 3-9**.

Proof: The proof process is complex, and the specific details are shown in the Appendix.

Theorem 3 indicates that when R_1 adopts high-level blockchain technology, R_1 can directly benefit from the demand growth brought by the blockchain effect, but the increase in profits is more complex, requiring a balance between price competition and market conditions. Notably, when the degree of channel competition is low, R_2 can also benefit from R_1 's blockchain strategy, resulting in a spillover effect of the blockchain. This occurs because, in a low-competition environment, R_1 and R_2 achieve demand alignment, meaning that R_1 , as the incumbent, and R_2 , as the new entrant, can clearly define their market positions. The price drop for R_2 has a more significant impact on its demand, thereby allowing R_2 to gain from the blockchain's spillover effect.

As shown in **Figure 3**, when the level of information asymmetry in the market is low, both R_1 's demand and profit, as well as R_2 's profit, increase with the rise in the degree of channel substitution, which is consistent with the conclusions of Theorem 1. Interestingly, when operational costs increase, R_1 's demand grows at a higher rate as channel substitution increases. This implies that increased channel competition brings more demand growth to R_1 . This is because, under higher operational costs, R_1 's demand becomes more sensitive to R_2 's price changes as the degree of channel substitution increases, leading to greater demand growth. However, due to negative price fluctuations and rising operational costs, the profit optimization R_1 gains from channel competition decreases as operational costs rise.

As shown in **Figure 4**, when R_1 experiences a high blockchain effect, R_1 's profit becomes more sensitive to the degree of channel substitution than its demand.

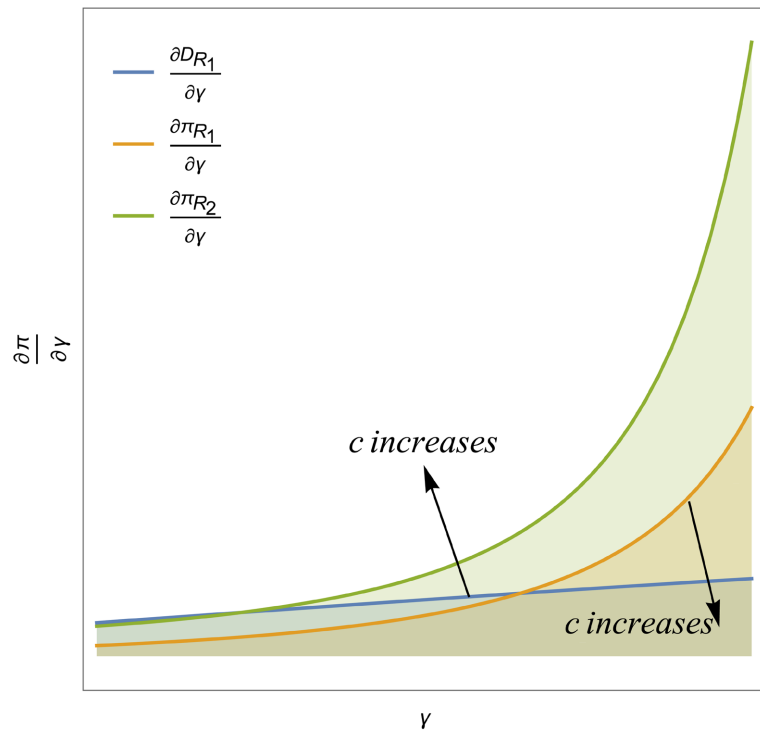


Figure 3. Sensitivity of γ at low q .

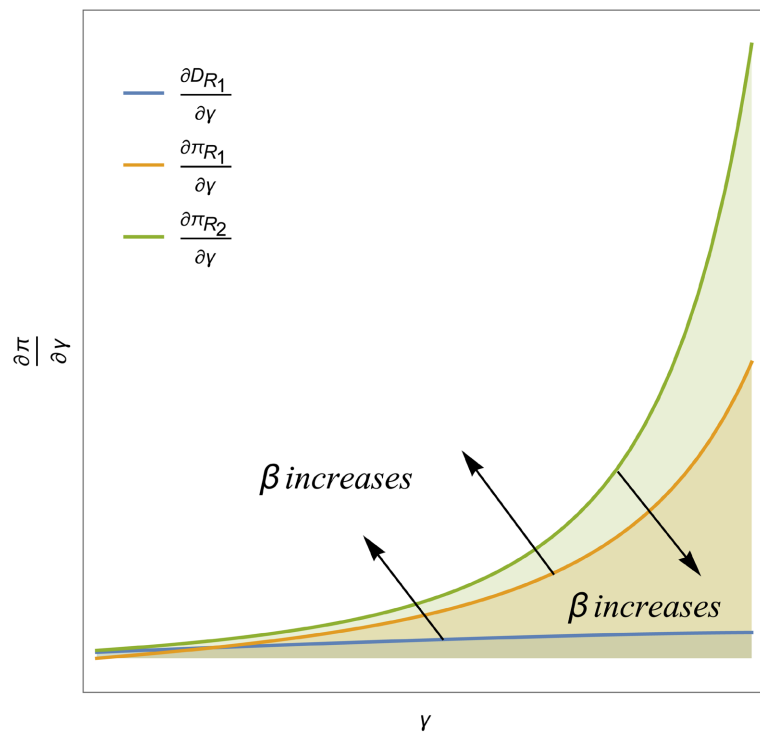


Figure 4. Sensitivity of γ at low q and high B .

This implies that even if the degree of channel substitution does not significantly boost R_1 's demand, R_1 can still achieve substantial profit growth. The underlying reason is that blockchain technology enhances information transparency, making

R_1 's products more trustworthy, which strengthens consumer confidence in R_1 's products. This enables R_1 to maintain high profitability even in a highly competitive market. Thus, with the support of the blockchain effect, R_1 can effectively reduce information asymmetry, increasing consumer trust and enhancing its product premium ability. Even in the face of intense market competition, R_1 can increase product value and transparency, thereby maintaining market share while generating higher profits. As the market's sensitivity to information asymmetry increases, R_2 's profit deteriorates due to its lack of blockchain technology for information disclosure, while R_1 capitalizes on R_2 's disadvantage to gain a greater competitive edge, optimizing both its demand and profit.

As shown in **Figure 5**, when the level of information asymmetry is high, the equilibrium results exhibit a negative change with increasing channel substitution degree. Even though R_1 is no longer directly affected by information asymmetry, it still suffers losses at low channel substitution degrees. This indicates that when information asymmetry is severe, R_2 is unable to compensate through channel competition, and an increase in channel substitution degree allows R_1 to capture R_2 's demand. Consequently, R_2 's demand decreases as the channel substitution degree increases at low levels. Additionally, R_1 is negatively impacted by R_2 's drastic price fluctuations under high information asymmetry, leading to R_1 also being affected by information asymmetry.

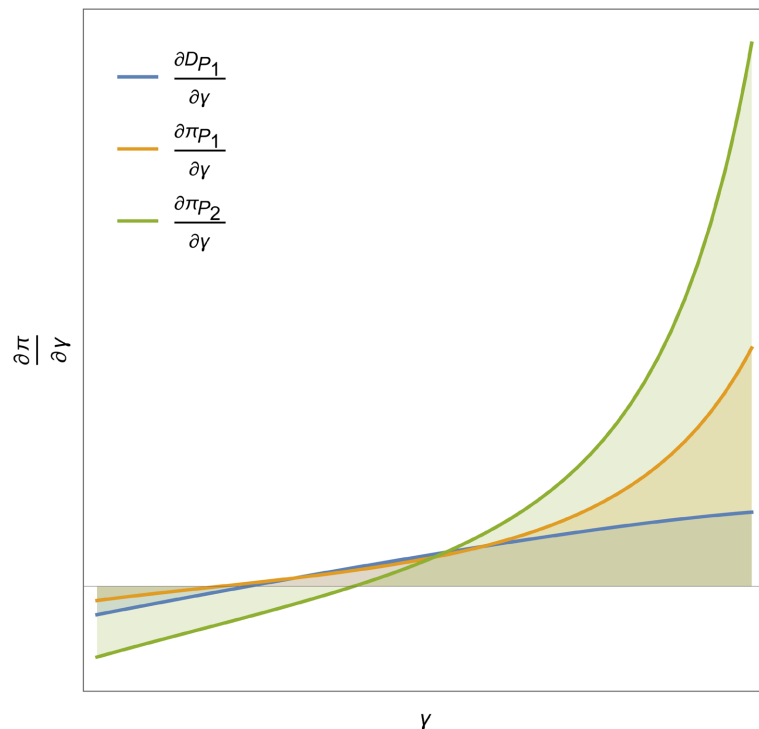


Figure 5. Sensitivity of γ at high q .

As shown in **Figure 6**, when consumer sensitivity to information asymmetry increases, both the supplier and R_2 suffer profit losses, while R_1 's profit increases

due to the blockchain effect. Interestingly, at higher sensitivity levels, R_2 's profit increases with sensitivity, which contrasts with the general conclusion. The higher the consumer sensitivity to information asymmetry, the lower R_2 's demand, leading R_2 to reduce prices to alleviate the demand loss. Once demand drops to a certain level, price adjustments slow down, and further increases in sensitivity gradually have a less negative or even positive impact on R_2 's profit.

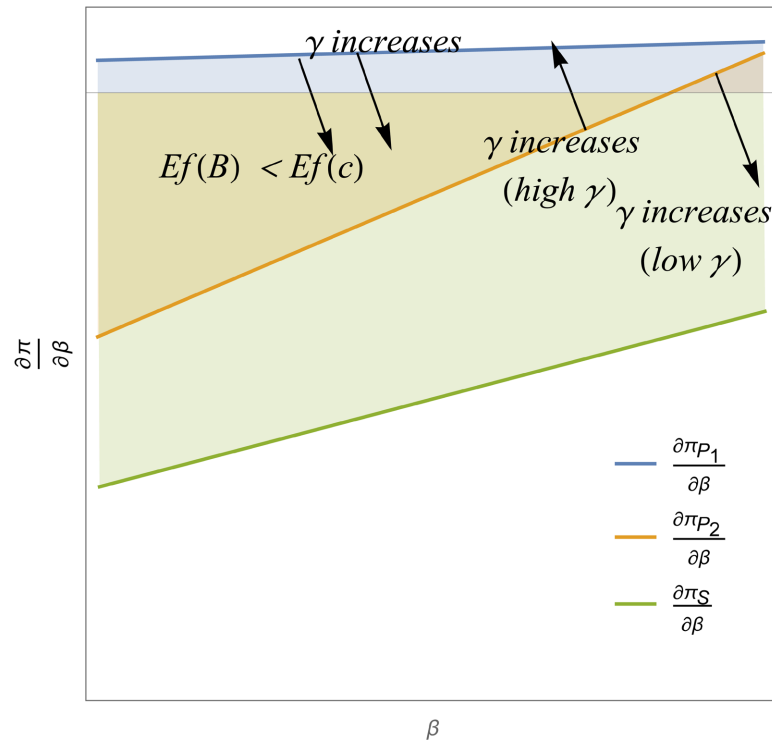


Figure 6. Sensitivity of β .

When the degree of channel substitution increases, a higher channel substitution degree helps R_2 capture more market share, while a lower substitution degree extends the process of reducing its demand to a certain threshold. Thus, a higher channel substitution degree promotes R_2 's profit optimization at high sensitivity levels, while a lower substitution degree suppresses it.

Furthermore, the $Ef(B) < Ef(c)$ indicates that when the profit increase from the blockchain effect is smaller than the blockchain costs (in the following text, we refer to this as low blockchain effect efficiency), R_1 cannot achieve sufficient profit growth from the blockchain, meaning that information asymmetry in the market continues to affect R_1 . As sensitivity increases, R_1 's profit declines. Similarly, as the channel substitution degree increases, R_1 and R_2 's products become more homogeneous, limiting R_1 's ability to benefit from the blockchain effect, which in turn restrains the profit optimization from increasing sensitivity.

As shown in **Figure 7**, since R_1 benefits from the blockchain effect, it can actually profit when information asymmetry in the market increases. However, when the degree of channel substitution decreases, R_1 's benefit from R_2 's price reduction

diminishes, thus suppressing the profit growth that would otherwise result from increasing information asymmetry. For R_2 , information asymmetry reduces its profit, but only when consumer sensitivity is high can R_2 , after its demand and price have dropped to a certain level, benefit from R_1 's higher price. Therefore, when the blockchain effect efficiency is small, R_1 's price decreases, leading to a corresponding decline in its profit.

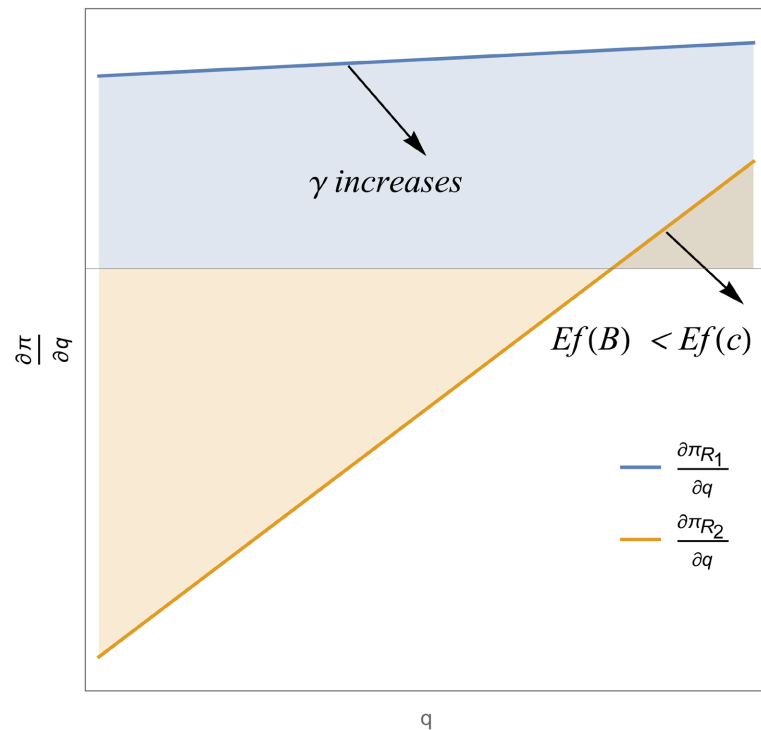


Figure 7. Sensitivity of q at high β .

As shown in **Figure 8**, both R_1 and the supplier S can achieve higher profits from the enhanced blockchain effect. Interestingly, R_2 also benefits from the enhanced blockchain effect when market information asymmetry is extremely high. This confirms the blockchain spillover effect mentioned earlier: when R_2 's losses from information asymmetry reach a certain threshold, the enhanced effect R_1 gains from blockchain technology prompts R_1 to raise its prices, which indirectly improves R_2 's competitive position. In other words, R_1 's price increase reduces consumers' willingness to choose its channel, giving R_2 a relative advantage in the intense competition.

Therefore, in markets with high information asymmetry, firms should not only focus on their own blockchain technology applications but also pay attention to competitors' reactions. Particularly under the influence of the blockchain spillover effect, firms can potentially strengthen their market competitiveness by employing precise pricing strategies and flexibly adjusting their competitive strategies.

As shown in **Figure 9**, when operational costs are sufficiently high, they suppress the impact of the blockchain effect, meaning that both R_1 and the supplier S

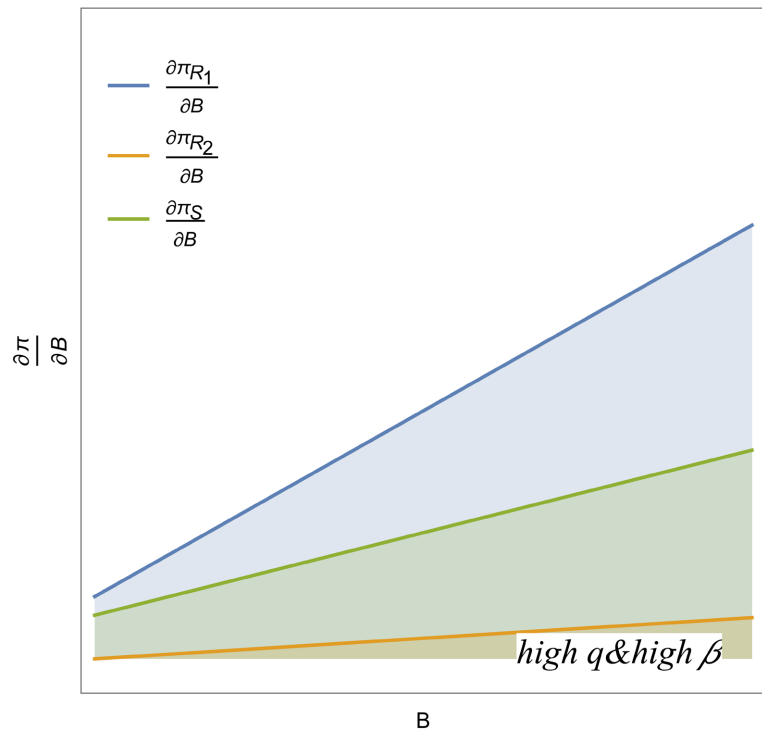


Figure 8. Sensitivity of B at low c .

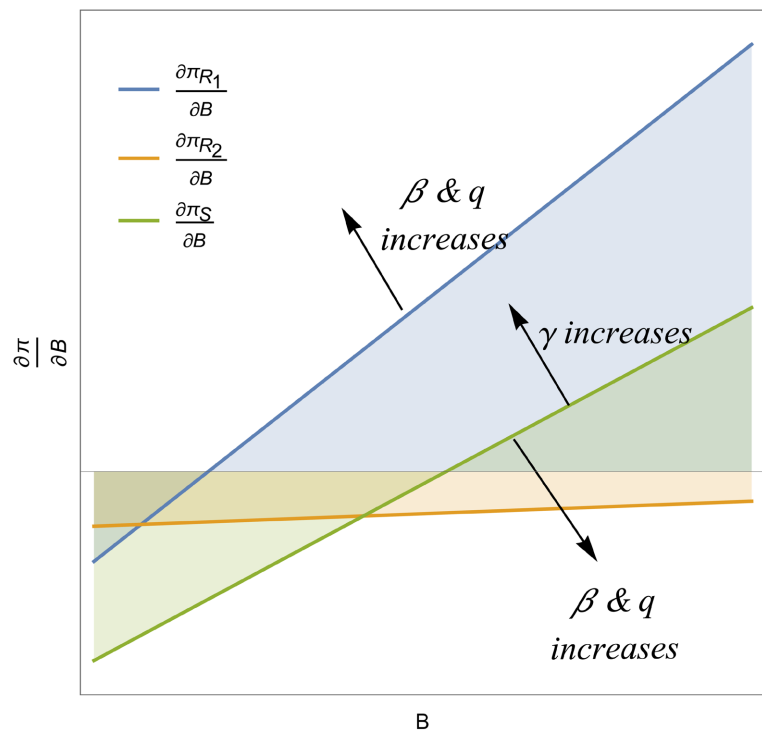


Figure 9. Sensitivity of B at high c .

only experience positive profit growth when the blockchain effect is strong. When overall market information asymmetry and consumer sensitivity increase, the blockchain effect for R_1 becomes more pronounced, further enhancing its impact

on R_1 's profits. However, when both information asymmetry and sensitivity increase simultaneously, the supplier S is negatively impacted by the reduction in R_2 's demand, which suppresses the positive impact of the blockchain effect on S 's profits. Additionally, the increase in the degree of channel substitution allows R_1 to capture the demand that R_2 loses due to information asymmetry, thereby increasing the overall market demand for the supplier and boosting its profits.

5.4. R_1 Adopts High-Level Blockchain Technology While R_2 Adopts Low-Level Blockchain Technology (HL)

When R_1 adopts high-level blockchain technology while R_2 adopts it at a low level, analyzing the impact of their different levels of application on the equilibrium outcomes becomes a crucial point. By solving Equations (13), (14), and (15) through backward induction, Lemma 5 is derived. The calculation process is shown in the Appendix.

$$\pi_S^{HL} = (\omega - c)(1 - p_{R_1} + \gamma p_{R_2} + B) + \omega(1 - p_{R_2} + \gamma p_{R_1}) \quad (13)$$

$$\pi_{R_1}^{HL} = (p_{R_1} - c)(1 - p_{R_1} + \gamma p_{R_2} + B) - F \quad (14)$$

$$\pi_{R_2}^{HL} = p_{R_2}(1 - p_{R_2} + \gamma p_{R_1} - \beta q) - F \quad (15)$$

Lemma 5. The equilibrium results of the HL strategy are as follows:

$$\omega^{HL*} = \frac{8 + 4\gamma - 3\gamma^2 - \gamma^3 + B(4 + 2\gamma - 2\gamma^2)}{2(8 - 4\gamma - 7\gamma^2 + 2\gamma^3 + \gamma^4)};$$

$$p_{R_1}^{HL*} = \frac{B(-40 + 8\gamma + 34\gamma^2 - 4\gamma^3 - 6\gamma^4) + (-8 - 4\gamma + 3\gamma^2 + \gamma^3)(6 - \gamma - 3\gamma^2 + 2c(2 - 2\gamma - \gamma^2 + \gamma^3))}{4(-1 + \gamma)(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)};$$

$$p_{R_1}^{HL*} = \frac{\left(\begin{aligned} &(-8 - 4\gamma + 3\gamma^2 + \gamma^3)(12 + (-2 + 4c)\gamma - (7 + 4c)\gamma^2 + (1 - 2c)\gamma^3 + 2c\gamma^4) \\ &- 2B(8 + 24\gamma - 12\gamma^2 - 19\gamma^3 + 4\gamma^4 + 3\gamma^5) \end{aligned} \right)}{8(-2 + \gamma^2)(8 - 4\gamma - 7\gamma^2 + 2\gamma^3 + \gamma^4)};$$

$$D_{R_1}^{HL*} = \frac{1}{8} \left(2 + \gamma + 2c(-2 + \gamma^2) + \frac{2B(-12 - 4\gamma + 5\gamma^2 + \gamma^3)}{-8 - 4\gamma + 3\gamma^2 + \gamma^3} \right);$$

$$D_{R_2}^{HL*} = \frac{-4 - 2(1 + 2c)\gamma + \gamma^2 + 2c\gamma^3 - \frac{2B(8 - 8\gamma - 12\gamma^2 + 3\gamma^3 + 3\gamma^4)}{-8 - 4\gamma + 3\gamma^2 + \gamma^3}}{8(-2 + \gamma^2)};$$

$$\pi_{R_1}^{HL*} = \frac{-\left(2B(-12 - 4\gamma + 5\gamma^2 + \gamma^3) + (-8 - 4\gamma + 3\gamma^2 + \gamma^3)(2 + \gamma + 2c(-2 + \gamma^2)) \right)^2}{32(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)^2} - F;$$

$$\pi_{R_2}^{HL*} = \frac{\left((-8 - 4\gamma + 3\gamma^2 + \gamma^3)(-4 - 2(1 + 2c)\gamma + \gamma^2 + 2c\gamma^3) - 2B(8 - 8\gamma - 12\gamma^2 + 3\gamma^3 + 3\gamma^4) \right)^2}{64(-2 + \gamma^2)^2(-8 - 4\gamma + 3\gamma^2 + \gamma^3)^2};$$

$$\pi_S^{HL*} = - \frac{\left(4B^2(2 + \gamma - \gamma^2)^2 + 4B(-8 - 4\gamma + 3\gamma^2 + \gamma^3)(-2 - \gamma + \gamma^2 + 2c(2 - 2\gamma - \gamma^2 + \gamma^3)) \right.}{16(-1 + \gamma)(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)} \left. + (-8 - 4\gamma + 3\gamma^2 + \gamma^3)(-8 - 4\gamma + 3\gamma^2 + \gamma^3 + 4c^2(-1 + \gamma)(-2 + \gamma^2)^2 + 4c(4 - 2\gamma - 4\gamma^2 + \gamma^3 + \gamma^4)) \right)$$

Theorem 4. Through sensitivity analysis of all equilibrium results in Lemma 4 with respect to the parameters β , γ , q and B , the following conclusions are obtained:

R_1 's demand is negatively correlated with γ and B only when

$$0 < \gamma < \frac{-1 + \sqrt{17}}{4} \ \& \ 0 < B < B_1^{HL} \ \& \ c_1^{HL} < c < 1.$$

S 's profit is negatively correlated with B only when

$$c_2^{HL} < c < 1 \ \& \ \left((0 < \gamma < \sqrt{0.182} \ \& \ 0 < B < 1) \ \parallel \ (\sqrt{0.182} < \gamma < \sqrt{0.393} \ \& \ 0 < B < B_2^{HL}) \right)$$

Proof: The proof process is complex, and the specific details are shown in the Appendix.

Theorem 4 indicates that only when the degree of channel substitution is low and the blockchain effect efficiency is minimal (i.e., low blockchain effect, high costs), R_1 does not gain from the increased channel substitution and blockchain effect. This means that when R_2 adopts blockchain technology to resolve information asymmetry, R_1 's low blockchain effect, combined with low channel substitution, prevents it from benefiting from competition. Instead, the increased channel substitution only allows R_2 to capture R_1 's market share. Furthermore, the enhanced blockchain effect causes R_1 to raise prices, leading to a loss of demand, and the blockchain effect at this point is insufficient to compensate for the loss.

For the supplier S , in the HN model, the increased blockchain effect helps it capture demand from R_1 's market side and increases its wholesale pricing power in R_2 's market side. However, in the HL model, when channel substitution is low and operational costs are high, S suffers as the blockchain effect increases. This is because S bears part of the operational costs, and with low channel substitution, R_1 's blockchain effect is limited, meaning that increasing the blockchain effect merely drives R_1 to raise prices, thereby reducing market demand on R_1 's side, which harms S 's profits. Therefore, when the channel substitution is moderate, a higher blockchain effect does not lead to this negative outcome. As the degree of channel substitution continues to rise, any increase in the blockchain effect enhances the supplier's profits.

Thus, supply chain members should carefully consider the interaction between the degree of channel substitution and the blockchain effect to maximize profits. Particularly when channel substitution is moderate, blockchain technology can optimize operations without harming demand. As the degree of channel substitution increases further, the blockchain effect significantly boosts supplier profits, warranting increased investment in blockchain technology.

6. Comparative Analysis

6.1. LN-NN

Theorem 5. Analysis of R_1 's low-level blockchain adoption strategy:

$$\begin{aligned} \omega_{R_1}^{LN*} > \omega_{R_1}^{NN*}; \quad p_{R_1}^{LN*} > p_{R_1}^{NN*}; \quad p_{R_2}^{LN*} > p_{R_2}^{NN*}; \quad D_{R_1}^{LN*} > D_{R_1}^{NN*}; \\ \pi_{R_1}^{LN*} > \pi_{R_1}^{NN*}; \quad \pi_S^{LN*} > \pi_S^{NN*}. \end{aligned}$$

When $\sqrt{0.595} < \gamma < 1$, $\pi_{R_2}^{LN*} > \pi_{R_2}^{NN*}$ and $D_{R_2}^{LN*} > D_{R_2}^{NN*}$.

Proof: The proof process is complex, and the specific details are shown in the Appendix.

By comparing the scenario where the incumbent retailer adopts blockchain technology, we observe a significant improvement in the overall performance of the supply chain, further demonstrating the necessity of introducing blockchain technology in the online fresh supply chain. This improvement is not limited to individual retailers' gains; suppliers also benefit, as increased transparency reduces market uncertainty, thereby enhancing the overall operational efficiency of the supply chain. However, R_2 inevitably suffers losses, and only when the degree of channel substitution is high enough can R_2 gain sufficient profit from R_1 's higher prices, leading to an increase in R_2 's profit. Given that R_1 has sufficient motivation to adopt blockchain technology, this paper focuses on the interaction between R_1 and R_2 under different blockchain adoption strategies. The following sections will specifically analyze the strategic interactions between R_1 and R_2 in this context.

6.2. LL-LN

Theorem 6. Analysis of R_2 's Low-Level Blockchain Adoption Strategy (Under R_1 's Low-Level Blockchain Adoption):

$$\omega_{R_1}^{LL*} > \omega_{R_1}^{LN*}; \quad p_{R_1}^{LL*} > p_{R_1}^{LN*}; \quad p_{R_2}^{LL*} > p_{R_2}^{LN*}; \quad D_{R_2}^{LL*} > D_{R_2}^{LN*}; \quad \pi_S^{LL*} > \pi_S^{LN*}.$$

When $\sqrt{0.681} < \gamma < 1$, $\pi_{R_1}^{LL*} > \pi_{R_1}^{LN*}$ and $D_{R_1}^{LL*} > D_{R_1}^{LN*}$. When $0 < F < F_1^{L-N}$, $\pi_{R_2}^{LL*} > \pi_{R_2}^{LN*}$.

Proof: The proof process is complex, and the specific details are shown in the Appendix.

When both R_1 and R_2 adopt low-level blockchain technology, a comparison with the LN-NN scenario reveals that R_1 needs a higher degree of channel substitution to benefit from R_2 's blockchain adoption strategy. Although R_1 has already adopted blockchain technology, positioning it similarly to R_2 in the LN-NN scenario, R_1 should theoretically have the first-mover advantage and be able to absorb more competitive losses. However, since R_1 has already implemented blockchain technology and is operating at a higher price, R_2 gains a price advantage. As a result, R_1 requires a higher degree of channel substitution to offset its competitive losses.

In the LN-NN case, R_1 will choose to adopt blockchain technology regardless of

the fixed blockchain costs, making blockchain an inevitable choice for R_1 (e.g., JD.com, Walmart). However, for new entrants like R_2 , the costs need to be carefully considered, as seen with some smaller retailers. This is because R_2 's pricing strategy is influenced by R_1 's decisions, making it difficult for R_2 to ignore the costs of implementing blockchain technology. Therefore, for new entrants like R_2 , the strategic decision to adopt blockchain must carefully weigh the costs and competitive landscape, especially when competing against established players like R_1 with a first-mover advantage.

If R_2 were to independently bear the high costs of blockchain adoption, it would entail significant risk. Hence, R_2 could consider collaborating with suppliers, technology providers, or other market participants to share the costs of blockchain adoption. By forming blockchain alliances, R_2 could benefit from the advantages of blockchain technology while reducing the burden of bearing the costs alone. For example, although Kroger is smaller than Walmart, it is a participant in a blockchain alliance, using IBM Food Trust technology with Walmart, Nestlé, and other supply chain members to enhance food safety and transparency.

6.3. HL-HN

Theorem 7. Analysis of R_2 's Low-Level Blockchain Adoption Strategy (Under R_1 's High-Level Blockchain Adoption):

$$\omega_{R_1}^{HL*} > \omega_{R_1}^{HN*}; p_{R_1}^{HL*} > p_{R_1}^{HN*}; p_{R_2}^{HL*} > p_{R_2}^{HN*}; D_{R_2}^{HL*} > D_{R_2}^{HN*}; \pi_S^{LN*} > \pi_S^{NN*}.$$

$$\text{When } \sqrt{0.681} < \gamma < 1, D_{R_1}^{HL*} > D_{R_1}^{HN*}. \text{ When } 0 < F < F_1^{L-N} \quad \pi_{R_2}^{HL*} > \pi_{R_2}^{HN*}.$$

$$0 < \beta < \frac{2}{3} \&\&$$

$$\text{When } \left(\begin{array}{l} \left(0 < \gamma < \sqrt{0.681} \&\& c_1^{HL-HN} < c < 1 \&\& 0 < B < B_1^{HL-HN} \right) \parallel \\ \sqrt{0.681} < \gamma < \frac{1}{4}(-1 + \sqrt{17}) \&\& \left(\left(0 < c < c_1^{HL-HN} \&\& 0 < B < 1 \right) \parallel \left(c_1^{HL-HN} < c < 1 \&\& B_1^{HL-HN} < B < 1 \right) \right) \\ \frac{1}{4}(-1 + \sqrt{17}) < \gamma < \gamma_1^{HL-HN} \&\& \left(\left(0 < B < 1 \&\& 0 < q < q_1^{HL-HN} \&\& 0 < c < 1 \right) \parallel \right. \\ \left. \left(q_1^{HL-HN} < q < 1 \&\& \left(\left(0 < B < 1 \&\& 0 < c < c_1^{HL-HN} \right) \parallel \right. \right. \right. \\ \left. \left. \left. \left(c_1^{HL-HN} < c < 1 \&\& B_1^{HL-HN} < B < 1 \right) \right) \right) \right) \\ \gamma_1^{HL-HN} < \gamma < 1 \&\& 0 < q < 1 \&\& 0 < c < 1 \&\& 0 < B < 1 \end{array} \right),$$

$$\pi_{R_1}^{HL*} > \pi_{R_1}^{HN*}.$$

Proof: The proof process is complex, and the specific details are shown in the Appendix.

In the case where R_1 has already adopted high-level blockchain technology, R_2 tends to adopt blockchain technology when the fixed cost of blockchain is low, to address market information asymmetry, which is consistent with the conclusion of Theorem 7.

The situation becomes more complex regarding R_1 's profit growth. Since there is no longer information asymmetry in the market, both R_1 and R_2 implement high-price strategies. Therefore, whether R_1 's profit increases depends on the interaction between its price and demand. When the degree of channel substitution is low, R_1 can only benefit from low blockchain effect efficiency, as R_1 cannot gain a market advantage through blockchain technology. However, as both R_1 and R_2 's prices rise, R_1 's demand decreases at a lower rate than its price increases, leading to profit growth for R_1 .

When the degree of channel substitution is moderate, R_2 's blockchain adoption strategy can enable R_1 to benefit from the blockchain effect, particularly when costs are low or blockchain effects are strong. This means that when there is no information asymmetry in the market and R_1 has a relative advantage, R_2 's strategy can optimize R_1 's profits, creating a win-win scenario.

As the degree of channel substitution further increases, and the level of information asymmetry in the market decreases, any blockchain effect can allow R_1 to benefit from R_2 's strategy. This is because, when the market information asymmetry is low, R_2 has a price advantage without adopting blockchain technology, and its market demand is not severely affected by information asymmetry. As a result, R_1 prefers R_2 to adopt blockchain technology and raise its price, thus reducing R_1 's competitive losses. Therefore, with a higher degree of channel substitution, R_2 's blockchain strategy can optimize R_1 's strategy under any circumstances.

6.4. HN-LN

Theorem 8. Analysis of R_1 's High-Level Blockchain Adoption Strategy (Under R_2 's Non-Adoption of Blockchain):

$$\omega^{HN*} > \omega^{LN*}; p_{R_1}^{HN*} > p_{R_1}^{LN*}; p_{R_2}^{HN*} < p_{R_2}^{LN*}.$$

When

$$\left(0 < B < \frac{4}{5} \& \& 0 < \gamma < 1 \& \& 0 < c < c_1^{H-L}\right) \parallel \left(\frac{4}{5} < B < 1 \& \& (0 < \gamma < \gamma_1^{H-L} \& \& 0 < c < c_1^{H-L}) \parallel (\gamma < \gamma_1^{H-L} < \gamma < 1 \& \& 0 < c < 1)\right),$$

$$D_{R_1}^{HN*} > D_{R_1}^{LN*}.$$

When $(\gamma_2^{H-L} < \gamma < \sqrt{0.595} \& \& c_2^{H-L} < c < 1) \parallel (\sqrt{0.595} < \gamma < 1 \& \& 0 < c < 1)$,

$$D_{R_2}^{HN*} > D_{R_2}^{LN*}.$$

When

$$(0 < \gamma < \sqrt{0.837} \& \& 0 < c < c_1^{H-L} \& \& 0 < B < 1) \parallel (\sqrt{0.837} < \gamma < 1 \& \& (0 < B < B_1^{H-L} \& \& 0 < c < c_1^{H-L}) \parallel (B_1^{H-L} < B < 1 \& \& 0 < c < 1)),$$

$$\pi_{R_1}^{HN*} > \pi_{R_1}^{LN*}.$$

Proof: The proof process is complex, and the specific details are shown in the Appendix.

As the degree of channel substitution further increases, and the level of information asymmetry in the market decreases, any blockchain effect can allow R_1 to benefit from R_2 's strategy. This is because, when the market information asymmetry is low, R_2 has a price advantage without adopting blockchain technology, and its market demand is not severely affected by information asymmetry. As a result, R_1 prefers R_2 to adopt blockchain technology and raise its price, thus reducing R_1 's competitive losses. Therefore, with a higher degree of channel substitution, R_2 's blockchain strategy can optimize R_1 's strategy under any circumstances.

When R_1 has already adopted low-level blockchain technology, whether it is motivated to further adopt blockchain despite the operational costs depends on market conditions and the blockchain effect efficiency. Notably, when the blockchain effect is strong, R_1 's demand does not necessarily increase. When the degree of channel substitution is low and operational costs are high, R_1 's demand may actually decrease. This is because, even with an enhanced level of blockchain adoption, R_1 cannot capture much of R_2 's market demand due to the low channel substitution. As a result, higher operational costs push R_1 's prices up, leading to reduced market demand.

R_2 can only benefit from R_1 's high-level blockchain adoption strategy when the degree of channel substitution is moderate and operational costs are high, or when the degree of channel substitution is high. This is because, under high channel substitution, R_2 can gain more demand through its price advantage, and as operational costs rise, R_1 's prices increase, allowing R_2 's demand to grow accordingly.

R_1 's profit is determined by the blockchain effect and the degree of channel substitution. When the degree of channel substitution is low and R_1 is less affected by R_2 's price, R_1 will generally increase its blockchain adoption level under low operational costs. However, as the degree of channel substitution increases, R_1 can only benefit if the blockchain effect is strong. When the blockchain effect is weak, R_1 's high-level blockchain adoption strategy offers limited profit enhancement and may lead to a price disadvantage, meaning R_1 would avoid adopting a high-level blockchain strategy.

As shown in **Figure 10** & **Figure 11**, when R_1 adopts high-level blockchain technology, R_2 can benefit when market information asymmetry is high. At this point, R_2 has a lower competitive advantage compared to R_1 , so R_2 hopes that R_1 increases its blockchain adoption to help R_2 maintain a price advantage. In cases where market sensitivity is high, R_2 may benefit from a higher degree of channel substitution and lower market information asymmetry (Region I). This is because, even when market information asymmetry is low, R_2 hopes to leverage R_1 's increased blockchain adoption to gain a price advantage and, through high channel substitution, maximize the competitive advantage gained from R_1 's price increases.

As shown in **Figure 12** & **Figure 13**, since the supplier bears half of the operational

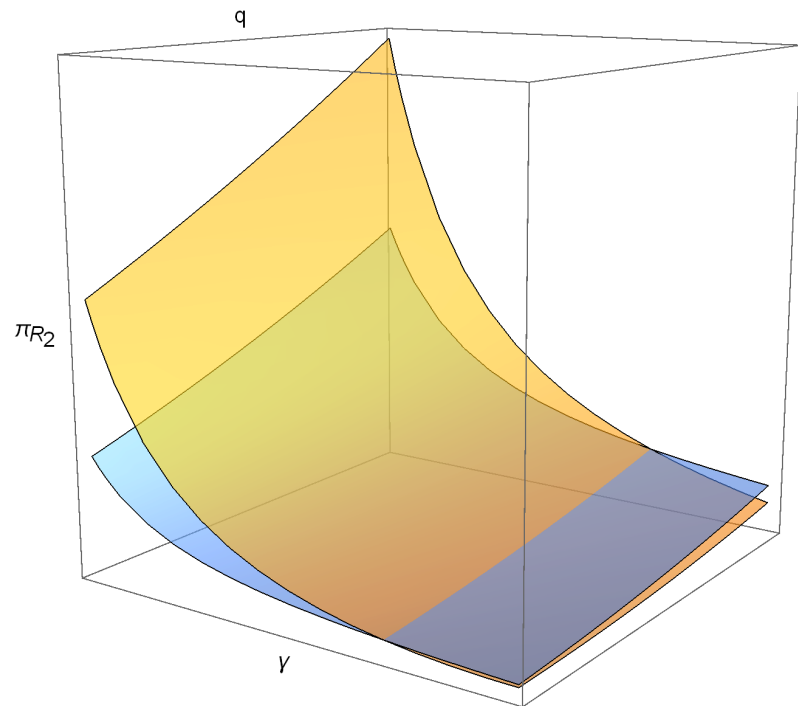


Figure 10. Comparison of R_2 's profit at low β .

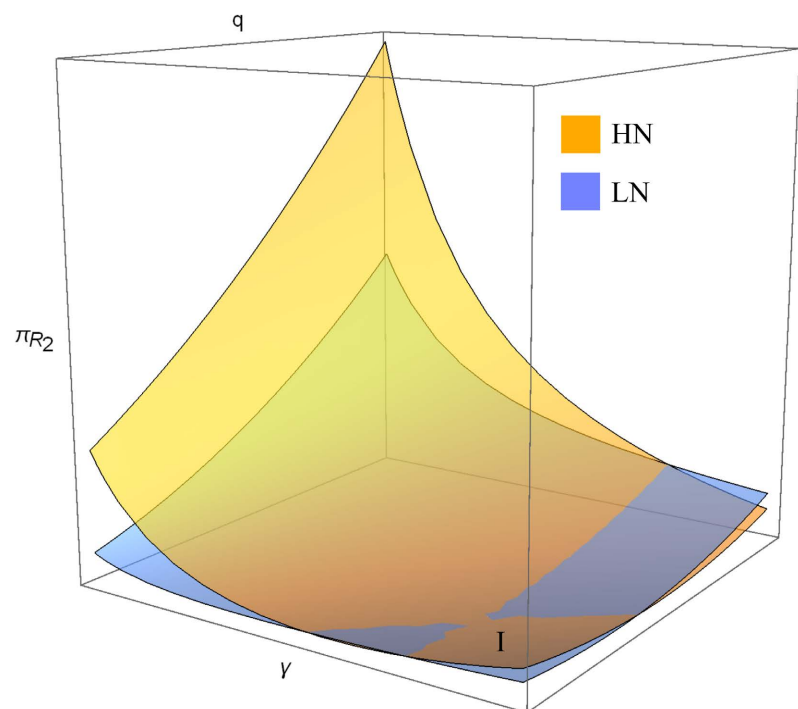


Figure 11. Comparison of R_2 's profit at high β .

costs, it becomes crucial to analyze how the blockchain effect impacts the supplier's profit. When the blockchain effect exceeds the cost losses of blockchain, the supplier prefers R_1 to increase its blockchain adoption level under low channel substitution and high market information asymmetry. In this case, with a lower

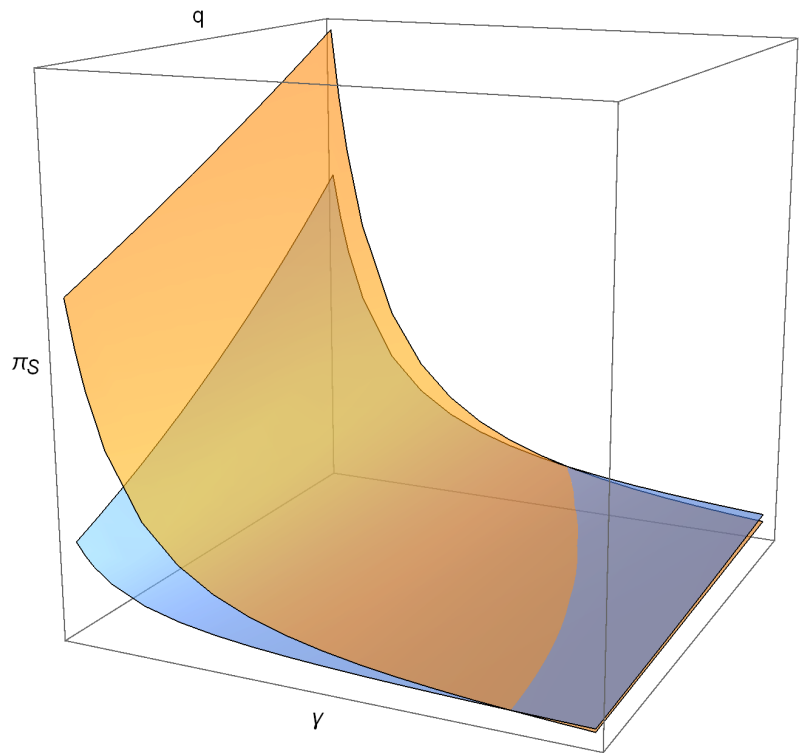


Figure 12. Comparison of S's profit ($Ef(B) > Ef(c)$).

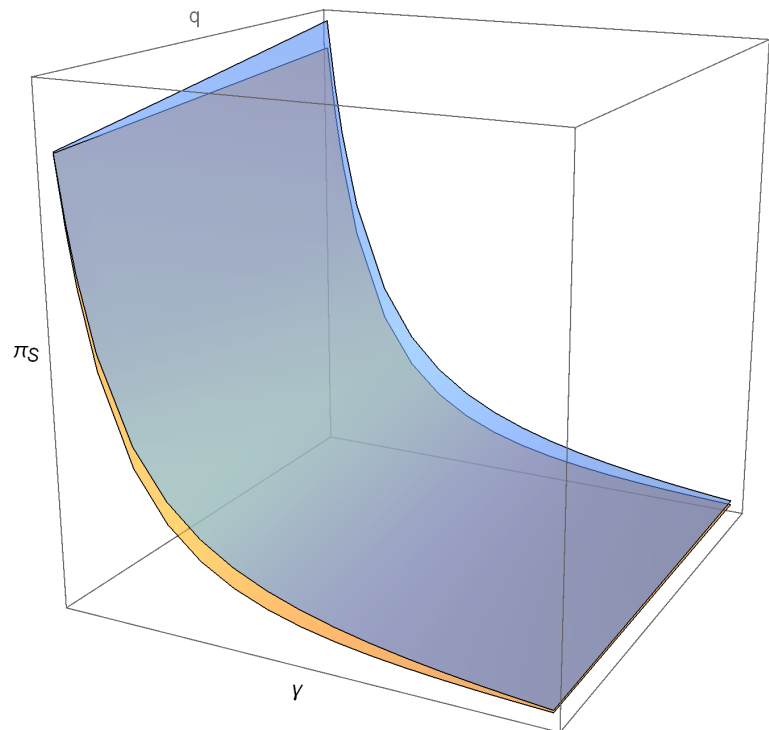


Figure 13. Comparison of S's profit ($Ef(B) < Ef(c)$).

channel substitution rate, the supplier hopes that R_1 increases its blockchain adoption to capture more market share without pushing R_2 out of the market due to

excessive channel similarity, thereby mitigating the negative effects of market information asymmetry. However, when the blockchain effect efficiency is small, R_1 's high-level adoption strategy provides no benefit to the supplier.

6.5. HL-LL

Theorem 9. Analysis of R_1 's High-Level Blockchain Adoption Strategy (Under R_2 's Adoption of Blockchain):

$$p_{R_2}^{HL*} > p_{R_2}^{LL*}.$$

$$(0 < \gamma < \sqrt{0.284} \ \& \ 0 < B < B_1^{HL-LL} \ \& \ c_1^{HL-LL} < c < 1) \parallel$$

$$\text{When } (\sqrt{0.284} < \gamma < \sqrt{0.595} \ \& \ 0 < B < 1 \ \& \ c_1^{HL-LL} < c < 1) \parallel, \ \pi_{R_2}^{HL*} > \pi_{R_2}^{LL*}.$$

$$(\sqrt{0.595} < \gamma < 1 \ \& \ 0 < B < 1 \ \& \ 0 < c < 1)$$

$$\text{When } (0 < \gamma < \gamma_1^{HL-LL} \ \& \ 0 < c < c_2^{HL-LL}) \parallel (\gamma_1^{HL-LL} < \gamma < 1 \ \& \ 0 < c < 1),$$

$$\pi_S^{HL*} > \pi_S^{LL*}.$$

The remaining analysis is consistent with Theorem 7 and will not be repeated here.

Proof: The proof process is complex, and the specific details are shown in the Appendix.

When R_1 increases its blockchain adoption level while R_2 adopts blockchain at a low level, R_1 's decision remains the same as when R_2 does not adopt blockchain. This implies that for R_1 , once it has a market advantage, the decision to increase blockchain adoption depends only on market conditions and competition with R_2 , while R_2 is more influenced by R_1 's strategy. Interestingly, in this situation, R_2 's price increases after R_1 raises its blockchain adoption level, indicating that once R_2 is no longer affected by information asymmetry, it can better adjust its pricing strategy based on R_1 's decisions. Moreover, even when blockchain effect efficiency is low, R_2 can still benefit from R_1 's strategy.

When the degree of channel substitution is low, R_2 hopes that R_1 increases its blockchain adoption strategy to gain from price competition. As the degree of channel substitution increases, the threshold for R_1 to boost R_2 's profit decreases, and when the degree of channel substitution is sufficiently high, R_2 benefits under all circumstances. This results in a blockchain spillover effect, where R_2 benefits from increased profits even without increasing its blockchain adoption level.

For the supplier S , when the degree of channel substitution is low and operational costs are high, S cannot benefit because R_1 's demand increment is smaller than R_2 's, and S still bears the high operational costs. However, as the degree of channel substitution increases, overall market demand grows, making the supplier willing to bear the operational costs to gain profit.

7. Conclusion

This paper constructs a competitive model of a fresh product supply chain, studying

the game structure among the supplier (S), the incumbent online retailer (R_1), and the new entrant online retailer (R_2). Due to consumers' inability to directly obtain true product quality information, information asymmetry exists, and this perception is influenced by consumers' quality sensitivity. Retailers can disclose true product quality information by introducing blockchain technology, thereby reducing the negative impact of information asymmetry on consumer trust. The incumbent retailer can choose to adopt blockchain technology at a high level, requiring suppliers to participate in a consortium blockchain and share information. By constructing different sub-models, this paper investigates the impact of varying degrees of blockchain technology application on the profits of supply chain members and market competitiveness.

The main conclusions are as follows: 1) Blockchain spillover effect: When only R_1 adopts blockchain technology at a high level, not only does R_1 directly benefit from reduced information asymmetry and increased demand, but the competitor R_2 may also benefit under certain circumstances. This spillover effect exists both at low and high levels of channel substitution: Low channel substitution: Blockchain technology enhances the trust of the entire market, indirectly promoting R_2 's demand growth. High channel substitution: Even if R_2 does not increase the level of blockchain application, it can profit from R_1 's high-price strategy. As R_1 raises its prices after enhancing blockchain application, R_2 can leverage price advantages to capture more market share. This indicates that even enterprises that have not fully applied blockchain technology can benefit from competitors' blockchain strategies under specific market conditions, reflecting the positive externalities in the supply chain. 2) Non-linear impact of consumer sensitivity and strategy adjustment: The study finds that consumers' sensitivity to information asymmetry has a non-linear effect on retailers' profits. When sensitivity is high, after R_2 's demand and price drop to a certain level, further increases in sensitivity can actually optimize its profit. This is because price changes tend to stabilize, and R_2 can benefit from R_1 's high pricing. Enterprises need to adjust pricing and blockchain strategies based on consumer sensitivity to maximize profits. 3) Balancing operating costs and blockchain effects: High operating costs may weaken the positive impact of blockchain effects on the profits of R_1 and S. However, when the blockchain effect is strong enough, it can offset the negative impact of high costs. At higher levels of channel substitution, suppliers are willing to bear operating costs because the overall market demand increases, enhancing the total supply chain profit. For R_2 , introducing blockchain technology requires considering high fixed costs. The conclusions suggest that cooperating with suppliers or other market participants to share the application costs of blockchain technology can reduce the risk of bearing high costs alone. This cooperative strategy helps R_2 enjoy the benefits of blockchain technology, achieving a win-win situation among supply chain members.

Based on the above conclusions, the following managerial insights are proposed:

1) Value the blockchain spillover effect and develop comprehensive strategies:

Enterprises should fully recognize the impact of blockchain technology on competitors and the entire market when considering its adoption. Leaders (R_1) need to enhance their own returns while guarding against potential competitive threats; weaker competitors (R_2) should closely monitor market dynamics, evaluate opportunities to benefit from competitors' blockchain strategies, and timely adjust their own strategies. 2) Optimize pricing and blockchain strategies based on consumer sensitivity: Enterprises should deeply understand target consumers' sensitivity to information asymmetry and flexibly adjust pricing and the degree of blockchain application according to different sensitivity levels. In markets with high sensitivity, effectively leveraging competitors' pricing strategies can optimize their own profits and enhance market competitiveness. 3) Balance operating costs and blockchain effects to ensure investment returns: When introducing blockchain technology, enterprises need to comprehensively assess operating costs and expected benefits, ensuring that the blockchain effect is sufficient to offset the impact of high costs. Suppliers and retailers should strengthen cooperation, jointly bear operating costs, and enhance the overall efficiency and profit of the supply chain. 4) Actively seek cooperation to achieve supply chain win-win: Enterprises (especially new entrant retailers) can collaborate with suppliers or other market participants to share the application costs of blockchain technology. This not only reduces individual cost burdens but also allows sharing technological achievements, enhancing the transparency and trust of the supply chain, ultimately achieving mutual benefits for all parties.

Future research can further explore: 1) The synergistic effects of blockchain technology for different stakeholders in a multi-party supply chain structure, as well as the application outcomes of various blockchain technology solutions in supply chains. 2) How consumer behavior and preferences influence the decision to introduce blockchain technology in supply chains, particularly its impact on demand fluctuations under different market conditions. 3) The application of blockchain technology in more complex supply chain structures, such as issues of information transparency in multi-tier or globalized supply chains.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Proof of lemma.

The optimal solutions for each sub-model are obtained using a backward induction method. Taking the NN strategy as an example, before analyzing the pricing strategy of the new entrant retailer (R_2), the pricing strategy of the incumbent retailer (R_1) is first analyzed. During the solution process, the second-order derivative of the incumbent retailer's profit function is calculated to obtain its optimal pricing solution. Next, the obtained optimal solution ($p_{R_1}(p_{R_1}, \omega)$) is substituted to solve the pricing decision of the new entrant retailer. Finally, the expression ($p_{R_1}(\omega)$ & $p_{R_2}(\omega)$) is substituted into the supplier's profit function to obtain the optimal wholesale price (ω^*), and the optimal pricing solution ($p_{R_1}^*; p_{R_2}^*$) is derived by substitution.

Proof of Theorem 1.

By taking derivatives of the equilibrium solutions obtained in Lemma 1 with respect to the relevant parameters, we obtain:

$$\begin{aligned} \frac{\partial \omega^{NN*}}{\partial \gamma} &= \frac{1-q\beta}{2(-1+\gamma)^2} > 0; \quad \frac{\partial \omega^{NN*}}{\partial q} = \frac{\beta}{2(-1+\gamma)} < 0; \quad \frac{\partial \omega^{NN*}}{\partial \beta} = \frac{q}{2(-1+\gamma)} < 0. \\ \frac{\partial p_{R_1}^{NN*}}{\partial \gamma} &= -\frac{(-1+q\beta)(10-13\gamma^2+2\gamma^3+3\gamma^4)}{4(-1+\gamma)^2(-2+\gamma^2)^2} > 0; \quad \frac{\partial p_{R_1}^{NN*}}{\partial q} = \frac{\beta(-6+\gamma+3\gamma^2)}{4(-1+\gamma)(-2+\gamma^2)} < 0; \\ \frac{\partial p_{R_1}^{NN*}}{\partial \beta} &= \frac{q(-6+\gamma+3\gamma^2)}{4(-1+\gamma)(-2+\gamma^2)} < 0. \quad \frac{\partial p_{R_2}^{NN*}}{\partial \gamma} = -\frac{(-1+q\beta)(12-2\gamma-7\gamma^2+\gamma^3)}{8(-1+\gamma)(-2+\gamma^2)} > 0; \\ \frac{\partial p_{R_2}^{NN*}}{\partial q} &= -\frac{\beta(12-2\gamma-7\gamma^2+\gamma^3)}{8(-1+\gamma)(-2+\gamma^2)} < 0; \quad \frac{\partial p_{R_2}^{NN*}}{\partial \beta} = -\frac{q(12-2\gamma-7\gamma^2+\gamma^3)}{8(-1+\gamma)(-2+\gamma^2)} < 0. \\ \frac{\partial D_{R_1}^{NN*}}{\partial \gamma} &= \frac{1}{8}(1-q\beta) > 0; \quad \frac{\partial D_{R_1}^{NN*}}{\partial q} = -\frac{1}{8}\beta(2+\gamma) < 0; \quad \frac{\partial D_{R_1}^{NN*}}{\partial \beta} = -\frac{1}{8}q(2+\gamma) < 0. \\ \frac{\partial D_{R_2}^{NN*}}{\partial \gamma} &= -\frac{(-1+q\beta)(2+2\gamma+\gamma^2)}{4(-2+\gamma^2)^2} > 0; \quad \frac{\partial D_{R_2}^{NN*}}{\partial q} = -\frac{\beta(-4-2\gamma+\gamma^2)}{8(-2+\gamma^2)} < 0; \\ \frac{\partial D_{R_2}^{NN*}}{\partial \beta} &= -\frac{q(-4-2\gamma+\gamma^2)}{8(-2+\gamma^2)} < 0. \quad \frac{\partial \pi_{R_1}^{NN*}}{\partial \gamma} = \frac{(-1+q\beta)^2(1+\gamma)(2+\gamma)}{8(-2+\gamma^2)^2} > 0; \\ \frac{\partial \pi_{R_1}^{NN*}}{\partial q} &= -\frac{\beta(-1+q\beta)(2+\gamma)^2}{16(-2+\gamma^2)} < 0; \quad \frac{\partial \pi_{R_1}^{NN*}}{\partial \beta} = -\frac{q(-1+q\beta)(2+\gamma)^2}{16(-2+\gamma^2)} < 0. \\ \frac{\partial \pi_{R_2}^{NN*}}{\partial \gamma} &= \frac{(-1+q\beta)^2(-4-2\gamma+\gamma^2)(2+2\gamma+\gamma^2)}{16(-2+\gamma^2)^3} > 0; \quad \frac{\partial \pi_{R_2}^{NN*}}{\partial q} = \frac{\beta(-1+q\beta)(-4-2\gamma+\gamma^2)^2}{32(-2+\gamma^2)^2} < 0; \\ \frac{\partial \pi_{R_2}^{NN*}}{\partial \beta} &= \frac{q(-1+q\beta)(-4-2\gamma+\gamma^2)^2}{32(-2+\gamma^2)^2} < 0. \quad \frac{\partial \pi_S^{NN*}}{\partial \gamma} = \frac{(-1+q\beta)^2(6+\gamma-5\gamma^2-\gamma^3+\gamma^4)}{4(-1+\gamma)^2(-2+\gamma^2)^2} > 0; \\ \frac{\partial \pi_S^{NN*}}{\partial q} &= -\frac{\beta(-1+q\beta)(-8-4\gamma+3\gamma^2+\gamma^3)}{8(-1+\gamma)(-2+\gamma^2)} < 0; \quad \frac{\partial \pi_S^{NN*}}{\partial \beta} = -\frac{q(-1+q\beta)(-8-4\gamma+3\gamma^2+\gamma^3)}{8(-1+\gamma)(-2+\gamma^2)} < 0. \end{aligned}$$

Proof of Theorem 2.

By taking derivatives of the equilibrium solutions obtained in Lemma 2 with respect to the relevant parameters, we obtain:

By solving $\frac{\partial D_{R_1}^{LN*}}{\partial q} = -\frac{\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4)}{8(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$, we obtain that when $0 < \gamma < \sqrt{0.681}$, we have $\frac{\partial D_{R_1}^{LN*}}{\partial q} > 0$. By

solving $\frac{\partial D_{R_1}^{LN*}}{\partial \beta} = -\frac{q(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4)}{8(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$, we obtain that when $0 < \gamma < \sqrt{0.681}$, we have $\frac{\partial D_{R_1}^{LN*}}{\partial \beta} > 0$.

By solving $\frac{\partial D_{R_1}^{LN*}}{\partial \gamma} = \frac{1}{8} - \frac{q\beta(96+80\gamma-40\gamma^2-40\gamma^3+5\gamma^4+6\gamma^5+\gamma^6)}{8(-8-4\gamma+3\gamma^2+\gamma^3)^2} < 0$, we obtain that when

$$\left(\left(\frac{16}{27} < \beta \leq \frac{2}{3} \ \&\& \ \gamma_1^{LN} < \gamma < 1 \ \&\& \ q_1^{LN} < q < 1 \right) \parallel \left(\sqrt{0.688} < \beta < 1 \ \&\& \ 0 < \gamma < 1 \ \&\& \ q_1^{LN} < q < 1 \right) \right) \\ \left(\left(\frac{2}{3} < \beta \leq \sqrt{0.688} \ \&\& \ q_1^{LN} < q < 1 \left((0 < \gamma < \gamma_1^{LN}) \parallel (\gamma_1^{LN} < \gamma < 1) \right) \right) \right)$$

We have $\frac{\partial D_{R_1}^{LN*}}{\partial \gamma} < 0$. And $q_1^{LN} = \frac{64+64\gamma-32\gamma^2-40\gamma^3+\gamma^4+6\gamma^5+\gamma^6}{96\beta+80\beta\gamma-40\beta\gamma^2-40\beta\gamma^3+5\beta\gamma^4+6\beta\gamma^5+\beta\gamma^6}$, γ_1^{LN} is too complex and will not be elaborated further here.

By solving $\frac{\partial D_{R_1}^{LN*}}{\partial \gamma} = -\frac{\left(\left((16+16\gamma-2\gamma^2-5\gamma^3-\gamma^4+q\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4)) \right) \right. \\ \left. \left((1+\gamma)(-8-4\gamma+3\gamma^2+\gamma^3)^2+q\beta(-96-48\gamma+72\gamma^2+20\gamma^3-21\gamma^4+3\gamma^6) \right) \right)}{8(-2+\gamma^2)^2(-8-4\gamma+3\gamma^2+\gamma^3)^3} < 0$, we obtain

that when $2/3 < \beta < 1 \ \&\& \ 0 < \gamma < \gamma_2^{LN} \ \&\& \ q_2^{LN} < q < 1$, we have $\frac{\partial D_{R_1}^{LN*}}{\partial \gamma} < 0$.

And $q_2^{LN} = \frac{-64-128\gamma-32\gamma^2+72\gamma^3+39\gamma^4-7\gamma^5-7\gamma^6-\gamma^7}{-96\beta-48\beta\gamma+72\beta\gamma^2+20\beta\gamma^3-21\beta\gamma^4+3\beta\gamma^6}$, γ_2^{LN} is too complex and will not be elaborated further here.

Proof of Theorem 3.

By taking derivatives of the equilibrium solutions obtained in Lemma 4 with respect to the relevant parameters, we

obtain: $\frac{\partial D_{R_1}^{HN*}}{\partial B} = \frac{-12-4\gamma+5\gamma^2+\gamma^3}{4(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$. By solving $\frac{\partial D_{R_2}^{HN*}}{\partial B} = \frac{-8+8\gamma+12\gamma^2-3\gamma^3-3\gamma^4}{4(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$, we obtain that

when $\sqrt{0.595} < \gamma < 1$, we have $\frac{\partial D_{R_2}^{HN*}}{\partial B} > 0$.

By solving $\frac{\partial D_{R_1}^{HN*}}{\partial \beta} = -\frac{\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4)}{8(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$, we obtain that when $0 < \gamma < \sqrt{0.681}$, we have $\frac{\partial D_{R_1}^{HN*}}{\partial \beta} > 0$.

By solving $\frac{\partial D_{R_1}^{HN*}}{\partial \beta} = \frac{\partial D_{R_1}^{HN*}}{\partial q} = -\frac{\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4)}{8(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$, we obtain that when $0 < \gamma < \sqrt{0.681}$, we have

$$\frac{\partial D_{R_1}^{HN*}}{\partial \beta} = \frac{\partial D_{R_1}^{HN*}}{\partial q} > 0.$$

Proof of Theorem 4.

By taking derivatives of the equilibrium solutions obtained in Lemma 4 with respect to the relevant parameters, we obtain:

By solving

$$\frac{\partial D_{R_1}^{HL*}}{\partial \gamma} = \frac{\left(\left(-(-8-4\gamma+3\gamma^2+\gamma^3)^2(-1-(1+2c)\gamma+c\gamma^3) + B(-32+80\gamma+104\gamma^2-52\gamma^3-60\gamma^4+7\gamma^5+10\gamma^6+\gamma^7) \right) \right)}{8(-2+\gamma^2)^2(-8-4\gamma+3\gamma^2+\gamma^3)^3} > 0$$

and $\frac{\partial D_{R_1}^{HL*}}{\partial B} = \frac{(-12-4\gamma+5\gamma^2+\gamma^3)(2B(-12-4\gamma+5\gamma^2+\gamma^3)+(-8-4\gamma+3\gamma^2+\gamma^3)(2+\gamma+2c(-2+\gamma^2)))}{8(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)^2} > 0$, We obtain that when $0 < \gamma < (-1+\sqrt{17})/4$ & $0 < B < B_1^{HL}$ & $c_1^{HL} < c < 1$, we have $\frac{\partial D_{R_1}^{HL*}}{\partial \gamma} > 0$ and $\frac{\partial D_{R_1}^{HL*}}{\partial B} > 0$, where

$$B_1^{HL} = \frac{-16+26\gamma^2+7\gamma^3-7\gamma^4-2\gamma^5}{-24-8\gamma+10\gamma^2+2\gamma^3},$$

$$c_1^{HL} = \frac{16+24B+16\gamma+8B\gamma-2\gamma^2-10B\gamma^2-5\gamma^3-2B\gamma^3-\gamma^4}{32+16\gamma-28\gamma^2-12\gamma^3+6\gamma^4+2\gamma^5}.$$

By solving $\frac{\partial \pi_s^{HL*}}{\partial B} = \frac{8B(2+\gamma-\gamma^2)^2+4(-8-4\gamma+3\gamma^2+\gamma^3)(-2-\gamma+\gamma^2+2c(2-2\gamma-\gamma^2+\gamma^3))}{16(-1+\gamma)(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$, we obtain that

when

$$c_2^{HL} < c < 1 \text{ \& } \left(0 < \gamma < \sqrt{0.182} \text{ \& } 0 < B < 1 \right), \text{ we have } \frac{\partial \pi_s^{HL*}}{\partial B} > 0, \text{ where}$$

$$\left\| \left(\sqrt{0.182} < \gamma < \sqrt{0.393} \text{ \& } 0 < B < B_2^{HL} \right) \right\|$$

$$B_2^{HL} = \frac{16-32\gamma-34\gamma^2+25\gamma^3+16\gamma^4-5\gamma^5-2\gamma^6}{8+8\gamma-6\gamma^2-4\gamma^3+2\gamma^4},$$

$$c_2^{HL} = \frac{-16-8B-16\gamma-8B\gamma+10\gamma^2+6B\gamma^2+9\gamma^3+4B\gamma^3-2\gamma^4-2B\gamma^4-\gamma^5}{-32+16\gamma+44\gamma^2-16\gamma^3-18\gamma^4+4\gamma^5+2\gamma^6}.$$

Proof of Theorem 5.

By comparing the equilibrium solutions of different sub-models and analyzing their relative magnitudes, we arrive at the conclusions of Theorems 5-8. To keep it concise, we only focus on the comparative analysis of models with threshold solutions.

By solving $D_{R_2}^{LN*} - D_{R_2}^{NN*} = \frac{q\beta(8-8\gamma-12\gamma^2+3\gamma^3+3\gamma^4)}{4(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$ and

$$\pi_{R_2}^{LN*} - \pi_{R_2}^{NN*} = \frac{q\beta(8-8\gamma-12\gamma^2+3\gamma^3+3\gamma^4)(-32-32\gamma+12\gamma^2+14\gamma^3-\gamma^4-\gamma^5+q\beta(40+24\gamma-24\gamma^2-11\gamma^3+4\gamma^4+\gamma^5))}{16(-2+\gamma^2)^2(-8-4\gamma+3\gamma^2+\gamma^3)^2} > 0$$

we obtain that when $\sqrt{0.595} < \gamma < 1$, $\pi_{R_2}^{LN*} > \pi_{R_2}^{NN*}$ and $D_{R_2}^{LN*} > D_{R_2}^{NN*}$.

Proof of Theorem 6.

By solving $D_{R_1}^{LL*} - D_{R_1}^{LN*} = \frac{q\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4)}{8(-8-4\gamma+3\gamma^2+\gamma^3)} > 0$ and

$$\pi_{R_1}^{LL*} - \pi_{R_1}^{LN*} = \frac{(-16-16\gamma+2\gamma^2+5\gamma^3+\gamma^4 - q\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4))^2}{32(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)^2} > 0$$

we obtain that when $\sqrt{0.681} < \gamma < 1$,

$$\pi_{R_1}^{LL*} > \pi_{R_1}^{LN*} \text{ and } D_{R_1}^{LL*} > D_{R_1}^{LN*}.$$

By solving

$$\pi_{R_2}^{LL*} - \pi_{R_2}^{LN*} = \frac{1}{64} \left(-64F + \frac{(-4-2\gamma+\gamma^2)^2}{(-2+\gamma^2)^2} - \frac{(32+32\gamma-12\gamma^2-14\gamma^3+\gamma^4+\gamma^5 - q\beta(48+16\gamma-36\gamma^2-8\gamma^3+7\gamma^4+\gamma^5))^2}{(-2+\gamma^2)^2(-8-4\gamma+3\gamma^2+\gamma^3)^2} \right) > 0$$

we obtain that when $0 < F < F_1^{L-N}$, we have $\pi_{R_2}^{LL*} - \pi_{R_2}^{LN*} > 0$. F_1^{L-N} is too complex and will not be elaborated further here.

Proof of Theorem 7.

By solving

$$\pi_{R_2}^{HL*} - \pi_{R_2}^{HN*} = \frac{\left(q\beta(8-8\gamma-8\gamma^2+3\gamma^3+\gamma^4) \left(\begin{matrix} -32-8q\beta-32\gamma+8q\beta\gamma+4\gamma^2+8q\beta\gamma^2+10\gamma^3-3q\beta\gamma^3+2\gamma^4-q\beta\gamma^4 \\ +4B(-12-4\gamma+5\gamma^2+\gamma^3)+4c(16+8\gamma-14\gamma^2-6\gamma^3+3\gamma^4+\gamma^5) \end{matrix} \right) \right)}{32(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)^2} > 0$$

we obtain that when

$$0 < \beta < \frac{2}{3} \&\&$$

$$\left(\begin{matrix} (0 < \gamma < \sqrt{0.681} \&\& c_1^{HL-HN} < c < 1 \&\& 0 < B < B_1^{HL-HN}) \parallel \\ \sqrt{0.681} < \gamma < \frac{1}{4}(-1+\sqrt{17}) \&\& ((0 < c < c_1^{HL-HN} \&\& 0 < B < 1) \parallel (c_1^{HL-HN} < c < 1 \&\& B_1^{HL-HN} < B < 1)) \\ \frac{1}{4}(-1+\sqrt{17}) < \gamma < \gamma_1^{HL-HN} \&\& \left(\begin{matrix} (0 < B < 1 \&\& 0 < q < q_1^{HL-HN} \&\& 0 < c < 1) \parallel \\ q_1^{HL-HN} < q < 1 \&\& \left(\begin{matrix} (0 < B < 1 \&\& 0 < c < c_1^{HL-HN}) \parallel \\ (c_1^{HL-HN} < c < 1 \&\& B_1^{HL-HN} < B < 1) \end{matrix} \right) \end{matrix} \right) \\ \gamma_1^{HL-HN} < \gamma < 1 \&\& 0 < q < 1 \&\& 0 < c < 1 \&\& 0 < B < 1 \end{matrix} \right),$$

we have $\pi_{R_1}^{HL*} > \pi_{R_1}^{HN*}$,

where $c_1^{HL-HN} = \frac{32+8q\beta+32\gamma-8q\beta\gamma-4\gamma^2-8q\beta\gamma^2-10\gamma^3+3q\beta\gamma^3-2\gamma^4+q\beta\gamma^4}{64+32\gamma-56\gamma^2-24\gamma^3+12\gamma^4+4\gamma^5}$,

$$B_1^{HL-HN} = \frac{32-64c+8q\beta+32\gamma-32c\gamma-8q\beta\gamma-4\gamma^2+56c\gamma^2-8q\beta\gamma^2-10\gamma^3+24c\gamma^3+3q\beta\gamma^3-2\gamma^4-12c\gamma^4+q\beta\gamma^4-4c\gamma^5}{-48-16\gamma+20\gamma^2+4\gamma^3}$$

$$q_1^{HL-HN} = \frac{32 - 52\gamma^2 - 14\gamma^3 + 14\gamma^4 + 4\gamma^5}{8\beta - 8\beta\gamma - 8\beta\gamma^2 + 3\beta\gamma^3 + \beta\gamma^4} \cdot \gamma_1^{HL-HN} \text{ is too complex and will not be elaborated further here.}$$

Proof of Theorem 8.

By solving $D_{R_1}^{HN*} - D_{R_1}^{LN*} = \frac{-16 - 16\gamma + 2\gamma^2 + 5\gamma^3 + \gamma^4 - q\beta(8 - 8\gamma - 8\gamma^2 + 3\gamma^3 + \gamma^4)}{8(-8 - 4\gamma + 3\gamma^2 + \gamma^3)} > 0$, we obtain that when

$$\left(0 < B < \frac{4}{5} \ \& \ 0 < \gamma < 1 \ \& \ 0 < c < \frac{12B + 4B\gamma - 5B\gamma^2 - B\gamma^3}{16 + 8\gamma - 14\gamma^2 - 6\gamma^3 + 3\gamma^4 + \gamma^5} \right) \parallel \left(\frac{4}{5} < B < 1 \ \& \ \left(0 < \gamma < \gamma_1^{H-L} \ \& \ 0 < c < \frac{12B + 4B\gamma - 5B\gamma^2 - B\gamma^3}{16 + 8\gamma - 14\gamma^2 - 6\gamma^3 + 3\gamma^4 + \gamma^5} \right) \parallel \right), \text{ we have } D_{R_1}^{HN*} - D_{R_1}^{LN*} > 0. \ \gamma_1^{H-L} \text{ is too}$$

$$\left(\gamma < \gamma_1^{H-L} < \gamma < 1 \ \& \ 0 < c < 1 \right)$$

complex and will not be elaborated further here.

By solving $D_{R_2}^{HN*} - D_{R_2}^{LN*} = \frac{B(-8 + 8\gamma + 12\gamma^2 - 3\gamma^3 - 3\gamma^4) + c\gamma(16 + 8\gamma - 14\gamma^2 - 6\gamma^3 + 3\gamma^4 + \gamma^5)}{4(-2 + \gamma^2)(-8 - 4\gamma + 3\gamma^2 + \gamma^3)} > 0$, we obtain that

when $\left(\gamma_2^{H-L} < \gamma < \sqrt{0.595} \ \& \ \frac{8B - 8B\gamma - 12B\gamma^2 + 3B\gamma^3 + 3B\gamma^4}{16\gamma + 8\gamma^2 - 14\gamma^3 - 6\gamma^4 + 3\gamma^5 + \gamma^6} < c < 1 \right) \parallel \left(\sqrt{0.595} < \gamma < 1 \ \& \ 0 < c < 1 \right)$, we have

$D_{R_2}^{HN*} - D_{R_2}^{LN*} > 0. \ \gamma_2^{H-L}$ is too complex and will not be elaborated further here.

By solving $\pi_{R_1}^{HN*} - \pi_{R_1}^{LN*} > 0$, we obtain that when

$$\left(0 < \gamma < \sqrt{0.837} \ \& \ 0 < c < c_1^{H-L} \ \& \ 0 < B < 1 \right) \parallel \left(\sqrt{0.837} < \gamma < 1 \ \& \ \left(0 < B < B_1^{H-L} \ \& \ 0 < c < c_1^{H-L} \right) \parallel \left(B_1^{H-L} < B < 1 \ \& \ 0 < c < 1 \right) \right), \ \pi_{R_1}^{HN*} > \pi_{R_1}^{LN*}. \text{ The threshold ex-}$$

pressions have already been presented earlier and will not be repeated here.

Proof of Theorem 9.

By solving

$$\pi_{R_2}^{HL*} - \pi_{R_2}^{LL*} = \frac{1}{64(-2 + \gamma^2)^2} \left(-(-4 - 2\gamma + \gamma^2)^2 + \frac{\left((-8 - 4\gamma + 3\gamma^2 + \gamma^3)(-4 - 2(1 + 2c)\gamma + \gamma^2 + 2c\gamma^3) - 2B(8 - 8\gamma - 12\gamma^2 + 3\gamma^3 + 3\gamma^4) \right)^2}{(-8 - 4\gamma + 3\gamma^2 + \gamma^3)^2} \right) > 0$$

we obtain that when

$$\left(0 < \gamma < \sqrt{0.284} \ \& \ 0 < B < B_1^{HL-LL} \ \& \ c_1^{HL-LL} < c < 1 \right) \parallel \left(\sqrt{0.284} < \gamma < \sqrt{0.595} \ \& \ 0 < B < 1 \ \& \ c_1^{HL-LL} < c < 1 \right) \parallel, \ \pi_{R_2}^{HL*} > \pi_{R_2}^{LL*}, \text{ where}$$

$$\left(\sqrt{0.595} < \gamma < 1 \ \& \ 0 < B < 1 \ \& \ 0 < c < 1 \right)$$

$$B_1^{HL-LL} = \frac{16\gamma + 8\gamma^2 - 14\gamma^3 - 6\gamma^4 + 3\gamma^5 + \gamma^6}{8 - 8\gamma - 12\gamma^2 + 3\gamma^3 + 3\gamma^4},$$

$$c_1^{HL-LL} = \frac{8B - 8B\gamma - 12B\gamma^2 + 3B\gamma^3 + 3B\gamma^4}{16\gamma + 8\gamma^2 - 14\gamma^3 - 6\gamma^4 + 3\gamma^5 + \gamma^6}.$$

$$B^2(2+\gamma-\gamma^2)^2 + c(-16+8\gamma+22\gamma^2-8\gamma^3-9\gamma^4+2\gamma^5+\gamma^6)(2+\gamma+c(-2+\gamma^2))$$

By solving $\pi_S^{HL*} - \pi_S^{LL*} = \frac{+B(-8-4\gamma+3\gamma^2+\gamma^3)(-2-\gamma+\gamma^2+2c(2-2\gamma-\gamma^2+\gamma^3))}{4(-1+\gamma)(-2+\gamma^2)(-8-4\gamma+3\gamma^2+\gamma^3)} > 0,$

we obtain that when $(0 < \gamma < \gamma_1^{HL-LL} \ \& \ 0 < c < c_2^{HL-LL}) \parallel (\gamma_1^{HL-LL} < \gamma < 1 \ \& \ 0 < c < 1),$

we have $\pi_S^{HL*} > \pi_S^{LL*},$ where $c_2^{HL-LL} = \frac{-2-2B-\gamma}{2(-2+\gamma^2)} - \frac{1}{2} \sqrt{\frac{\left(32+16B^2+16\gamma-64B\gamma-32B^2\gamma-36\gamma^2-32B\gamma^2-16B^2\gamma^2-24\gamma^3+24B\gamma^3+16B^2\gamma^3+5\gamma^4+8B\gamma^4+6\gamma^5+\gamma^6\right)}{(-2+\gamma^2)^2(8-4\gamma-7\gamma^2+2\gamma^3+\gamma^4)}}.$