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Enhancing Fresh Supply Chain Performance: Examining Vertical Integration Strategies Through the Implementation of Blockchain Technology

Abstract. *Using a differential game model, this study examines the optimal pricing decisions, technology levels, and total profits under different integration strategies before and after blockchain implementation. The findings reveal that in the duopoly competition among fresh product retailers, the retail price of the retailer preferred by consumers tends to be higher, while the other is lower. Technology level within the vertical alliance varies with consumers' preference for a specific retailer. Retailers' competitive advantage leads to higher pricing for all participants and drives technology upgrades within the alliance. Blockchain implementation results in a decrease in wholesale price but an increase in retail prices. Moreover, consumers' heightened perception of fresh quality serves as a motivation for technology advancements and enhances fresh quality goodwill in the chain. Only when the deployment cost is sufficiently small can the manufacturer and the fresh supply chain achieve long-term benefits from blockchain adoption. Our study provides valuable insights for manufacturers in making informed decisions about the optimal strategy for adopting blockchain technology in the context of fresh supply chains.*

Keywords: *fresh supply chain, price competition, quality information asymmetry, blockchain technology, differential game.*

JEL Classification: C63, C70, Q11.

1. Introduction

The fresh market is characterised by a high uncertainty for the perishable nature and short shelf life of the products (Liu et al., 2023). Enterprises need to utilise cold chain logistics with preservation technology to maintain the freshness of fresh

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products in a low-temperature environment from the place of origin to the place of sale. This can satisfy consumers' preference for fresh product quality and promote an increase in market sales (Haiju et al., 2024). Chinese fresh product market sales reached 1.25 trillion yuan in 2019 with year-on-year increase 8.9%. And the scale of China's fresh retail market is expected to reach 2.5 trillion yuan by 2025. which requires high operating capacity of enterprises and fierce competition in the fresh industry. In the face of the highly dispersed fresh channels and fierce competition, the appropriate integration strategy is essential to reduce costs and improve economic efficiency. Vertical integration, which allows for alignment of natural interests within the supply chain, is becoming a popular channel strategy to improve enterprises' profitability and ensure high-quality products offered at competitive prices (Devos & Li, 2021).

For fresh companies, the acquisition and maintenance of a low-temperature environment requires a large amount of energy consumption and greenhouse gas emissions; greenhouse gases come from cold chain logistics accounts for 14% of global greenhouse gases (Qu & Wu, 2021). Therefore, how to make effective corporate decisions under the constraints of carbon reduction policies, in order to cope with the severe pressure of carbon reduction while simultaneously achieving optimal profitability, has become a common concern for both businesses and scholars (Zihan et al., 2024). (Xin et al., 2024) only takes into account the freshness of the fresh product, but fresh food companies should strike a balance between preservation and carbon reduction technologies. while fresh manufacturers implement preservation technology, retailers can upgrade their carbon reduction technology to ensure product freshness standards and control carbon emission levels. Manufacturers can preserve the freshness of products through dehydration, refrigeration, freezing, heating or radiation, and other technologies. Retailers can make efforts to reduce carbon emissions during the sales process. Both parties work together to improve the quality level of fresh produce, maximise profits and operational efficiency, and promote public welfare.

However, the actual condition of fresh products perceived by consumers does not always match the so-called high quality. Consumers may still be misled by behaviours such as concealing quality levels (Cozzio et al., 2023). Characterised by decentralised, tamper-proof, and traceable features, the blockchain has shown promising applications in the fresh supply chain. More importantly, the blockchain technology could not only help display and ensure the true quality of fresh products to consumers, but also contribute to restraining carbon emissions via tracking carbon footprints during the whole product life cycle. Platforms also began deploying blockchain technology to disclose the fresh quality more efficiently (Tan et al., 2023). For instance, Wal-Mart had openly disclosed the application of blockchain in the lettuce supply chain to mitigate product contamination risks, thus guaranteeing the prime quality of their vegetables.

In order to solve the existing problems of enterprise competition, product quality, and information asymmetry in the fresh food supply chain, this paper uses a differential game model to explore the impact of different vertical integration strategies on the performance of the fresh food supply chain under oligopolistic competition from a long-term perspective, and studies how the introduction of blockchain technology affects decision-making within the fresh food supply chain.

The objectives of this paper are: (1) Help business managers make informed decisions about fresh preservation and carbon reduction technology investments, as well as product quality improvement plans in competitive fresh supply chains; (2) Inspire business managers to adopt approaches such as vertical integration strategies to integrate and coordinate fresh supply chains in order to achieve excess profits; (3) Evaluate the adoption conditions of blockchain technology under different vertical integration strategies to ensure that the combination of integration strategy within the fresh supply chain and the implementation of blockchain will benefit the fresh supply chain most.

2. Literature Review

2.1 Vertical Integration Strategy

The vertical integration strategy has been used in various industries, such as the recycling platform, the online second-hand platform, and the medical electronic health records system (Qiu et al., 2023). Vertical integration, whether forward and backward, has become a channel strategy many manufacturers adopt to improve their profitability. Regardless of the degree of monopoly power, rewards under vertically integrated systems are higher than benefits under vertically separated systems (Lai et al., 2010). In the three-tier supply chain between retailers, service providers, and manufacturers, vertical integration strategies can provide more cost-effective guidance for retailers under different business modes (P. Li et al., 2021). Vertical integration strategies could also effectively protect enterprises' brand from illegal counterfeiting and create more values (Bian et al., 2023) .

Business modes, sales mode, degree of monopoly, and power structures in the chain could influence the usage of vertical integration strategy(Hu et al., 2021). Research also indicates that the forward integration of retailers could bring about a win-win situation (Li & Chen, 2020). At the moment, the manufacturing industry could use the ISA-95 model in the digital transformation process by adding connection layers and implementing vertical integration strategies. This process could help companies develop more effective digital transformation strategies (Apilioğulları, 2022). The World Customs Organisation had also developed an interface public member that enables firms' vertical integration to track the authenticity of products based on real-time data.

2.2 Blockchain Technology in fresh supply chain

The emergence of blockchain-based supply chain management has enabled the establishment of decentralised shared ledgers, self-governing digital agreements, and dependable and secure networks. Numerous studies have examined the effect of blockchain implementation from the perspective of the expense, quality, speed, reliability, sustainability, and flexibility in the supply chain management (Hastig & Sodhi, 2020). The new technology could provide consumers with reliable quality information of fresh products in the form of blockchain labels. This tamper proof traceability method could foster positive products preference, avoid quality fraud, and ultimately promote sales (Saberi et al., 2019) . Blockchain is more likely implemented upon consumers' heightened traceability awareness (Tan et al., 2023). Overall, blockchain technology could enhance the transparency of the fresh supply chain, increase consumers' trust, and stimulate sales (Cozzio et al., 2023).

For the realisation of the carbon reduction target, the government and enterprises all over the word have invested a lot in advanced technologies (Hailemariam et al., 2022; Yue et al., 2023). More and more fresh enterprises embark on developing blockchain platforms to track carbon footprints and reduce carbon emissions (Pu & Lam, 2021). For example, Wanxiang Blockchain strategically cooperated with China Quality Certification Group to build the carbon footprint traceability system. IBM and Veridium Labs have already partnered to tokenise carbon credits to help companies measure carbon emissions and trade credits. VeChain also built the powerful Digital Carbon Footprint SaaS Service tool, which enables enterprises of all sizes to re-engineer their carbon footprint data management practices. Therefore, fresh enterprises are embracing the development of blockchain technology for a "carbon abatement effect" (Li et al., 2023).

Therefore, this paper considers the vertical integration strategy of fresh supply chain, and introduces blockchain technology to analyse the vertical integration or decentralisation strategy adopted by competitive retailers, and discusses the optimal strategy set.

3. Model Description

3.1 Problem Description

This paper investigates the fresh supply chain that comprises one manufacturer and two competitive retailers. The manufacturer takes charge of freshness-keeping technology in the production process, while retailers use carbon abatement technologies during the distribution and inventory. The pricing strategy of competitive retailers has always been the most important issue in supply chain management (Choi, 1996). Moreover, it is also an important issue for the fresh supply chain to decide whether to build its own blockchain platform for quality and carbon footprint traceability. Figure 1 shows the fresh supply chain with price competition, in which the manufacturer adopts freshness-keeping technology, and the retailers undertake the carbon abatement target. Once the fresh supply chain implements blockchain technology, additional costs are required from the fresh manufacturer and retailers.

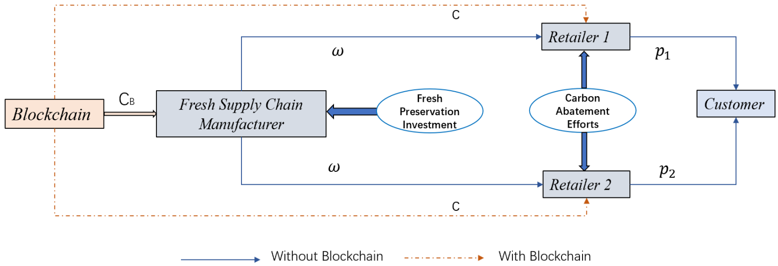

Figure 1. Fresh supply chain with price competition
Source: Authors' own creation.

3.2 Basic Assumptions

At time t, the manufacturer's freshness-keeping technology level is $L(t)$. The carbon abatement level of retailer 1 is $F_1(t)$, and that of retailer 2 is $F_2(t)$. k_1, k_2, k_3 are the cost coefficients of the manufacturer, retailer 1 and retailer 2. Similarly as with Bai et al. (2018), the investment of these technologies from the manufacturer and two retailers is high.

$$C_M(t) = \frac{k_1}{2}L^2(t),\ \ C_{R_1}(t) = \frac{k_2}{2}{F_1}^2(t),\ \ C_{R_2}(t) = \frac{k_3}{2}{F_2}^2(t) \tag{1}$$

Companies investing in research and development of preservation technologies and carbon reduction technologies can improve the freshness of fresh products (Ranjan & Jha, 2022), although the fresh quality of fresh products still naturally declines over time. Similar to Nerlove and Arrow (1962), the dynamic evolution of the fresh quality goodwill is

$$\dot{G}(t) = \xi_i\big(\alpha L(t) + \beta_1 F_1(t) + \beta_2 F_2(t)\big) - \eta G(t), i = N, Y \tag{2}$$

where α, β_1, β_2 are the influence coefficient of these technologies on fresh quality, and η is the natural decay rate of the goodwill. When blockchain is implemented, consumers definitely obtain the complete and accurate information on fresh quality with probability $\xi_Y = 1$. If not, they could just receive the total information with probability $\xi_N (0 < \xi_N < 1)$.

Higher fresh quality goodwill always indicates widespread acceptance from consumers, which determines the total market demand. Suppose the size of fresh market is a. Consumers will purchase fresh products from retailer 1 with probability s and retailer 2 with probability $1 - s$. $p_1(t)$ and $p_2(t)$ represent their retail price, respectively. Assume two retailers bulk purchase products from one manufacturer with the same wholesale price $\omega(t)$ in the fresh supply chain. Demand of the retailers depends on competitive advantage, fresh quality goodwill, and retail pricing. Similar with Liu et al. (2015) and Liu et al. (2021), we construct the demand function of two retailers considering pricing and non-pricing factors. Assume the competitive advantage of two retailers is the same, denoting as μ $(0 < \mu < 1)$. Thus, the market demand for two retailers at time t is

$$\begin{cases} D_1(t) = [sa - p_1(t) + \mu p_2(t)]kG(t) \\ D_2(t) = [(1-s)a - p_2(t) + \mu p_1(t)]kG(t) \end{cases} \tag{3}$$

Manufacturers, who are generally responsible for the initial stages of production, decide on whether to implement the infrastructures of blockchain technology. Assume the manufacturer's fixed deployment cost is C_B. The unit cost of blockchain usage for each retailer is c. Thus, the variable cost of blockchain usage of each retailer

$$C_{b_i} = cD_i(t), i = 1, 2 \tag{4}$$

Suppose that in an infinite period of time, the fresh supply chain does not introduce a blockchain, and the wholesale price ω^N and retail price p_i^N of the product are agreed within the supply chain, and they all have the same discount rate $\rho(0 < \rho < 1)$. The long-term profits of manufacturers and competitive retailers in the fresh supply chain are as follows：

$$\begin{cases} \max\limits_{\omega^N, L(t)} \pi_M = \int_0^\infty e^{-\rho t} \left\{ \omega^N [a - (1-\mu)(p_1^N + p_2^N)]kG(t) - \frac{k_1}{2} L^2(t) \right\} dt \\ \max\limits_{p_1^N, F_1(t)} \pi_{R_1} = \int_0^\infty e^{-\rho t} \left\{ (p_1^N - \omega^N)[sa - p_1^N + \mu p_2^N]kG(t) - \frac{k_2}{2} {F_1}^2(t) \right\} dt \\ \max\limits_{p_2^N, F_2(t)} \pi_{R_2} = \int_0^\infty e^{-\rho t} \left\{ (p_2^N - \omega^N)[(1-s)a - p_2^N + \mu p_1^N]kG(t) - \frac{k_3}{2} {F_2}^2(t) \right\} dt \end{cases} \tag{5}$$

Suppose that in an infinite period of time, the fresh supply chain introduces a blockchain, and the wholesale price ω^Y and retail price p_i^Y of the product are agreed within the supply chain, and they all have the same discount rate $\rho(0 < \rho < 1)$. The long-term profits of manufacturers and competitive retailers in the fresh supply chain are as follows:

$$\begin{cases} \max\limits_{\omega^Y, L(t)} \pi_M = \int_0^\infty e^{-\rho t} \left\{ \omega^Y [a - (1-\mu)(p_1^Y + p_2^Y)]kG(t) - \frac{k_1}{2} L^2(t) - C_B \right\} dt \\ \max\limits_{p_1^Y, F_1(t)} \pi_{R_1} = \int_0^\infty e^{-\rho t} \left\{ (p_1^Y - \omega^Y - c)[sa - p_1^Y + \mu p_2^Y]kG(t) - \frac{k_2}{2} {F_1}^2(t) \right\} dt \\ \max\limits_{p_2^Y, F_2(t)} \pi_{R_2} = \int_0^\infty e^{-\rho t} \left\{ (p_2^Y - \omega^Y - c)[(1-s)a - p_2^Y + \mu p_1^Y]kG(t) - \frac{k_3}{2} {F_2}^2(t) \right\} dt \end{cases} \tag{6}$$

3.3 Model construction

The manufacturer can choose whether to vertically integrate with competitive retailers, and there exist four combinations (see Table 2): Double decentralised strategy (Model-DD) (such as small, medium, and micro enterprises), Mixed strategy (Model-CD and Model-DC), and Double centralised strategy (Model-CC) (such as Haier Group and ZARA). Figure 2 shows the combination of four vertical integration strategies with blockchain implementation in the fresh supply chain.

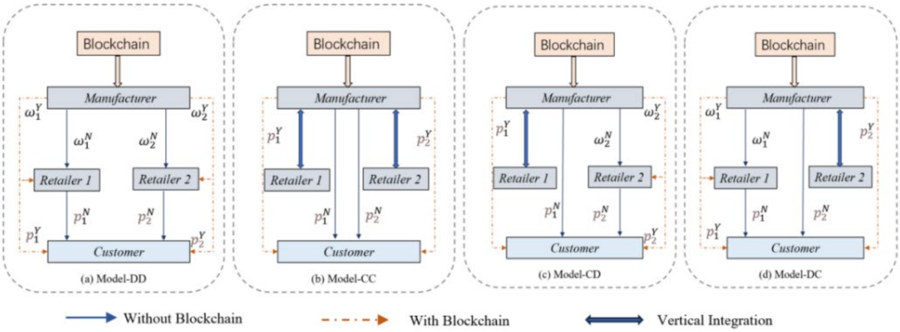

Figure 2. Vertical integration strategies with blockchain implementation in the fresh supply chain
Source: Authors' own creation.

In this study, considering the combination of the vertical integration strategy and blockchain implementation, we use the differential game model to investigate pricing strategy and strategic technologies investment in the competitive fresh supply chain from the long-term perspective. Furthermore, we assume the discount factor of long-term profit of the manufacture and retailers are the same, denoting as $\rho(0 < \rho < 1)$, and omit (t) from all formulas.

If there exists any vertical integration in the fresh supply chain, we could just calculate the total profit of the alliance (V_A) and the profit of retailer outside the alliance (V_B). However, for the double-decentralised strategy, we could calculate the profit of manufacturer (V_M), retailer 1 (V_{R_1}) and retailer 2 (V_{R_2}) individually. In the whole paper, we regard freshness-keeping technology level and carbon abatement technology level together as technology level in the fresh supply chain. Due to space limitations, the profit expression and the same equilibrium solution will not be repeated below.

3.3.1 General Model without Blockchain technology

I Double Decentralised Strategy (Model-DDN)

In the double decentralised strategy, the fresh manufacture will not vertically integrate with ang retailer. Competitive retailers are involved in the Cournot duopoly game, which constitutes a horizontal Nash competition. Firstly, the manufacturer sets the wholesale price ω^{DDN} and decides the freshness-keeping technology L^{DDN}. Then, two retailers independently determine their retail price $p_i^{DDN}(i = 1, 2)$ and carbon abatement level F_i^{DDN} $(i = 1, 2)$. Both sides in the fresh supply chain make decisions to maximise their benefits.

Theorem 1. In the double decentralised strategy without blockchain, the optimal strategies of the manufacturer and two competitive retailers within the fresh supply chain are as follows.

(1) Optimal decisions for the fresh supply chain:

$$\omega^{DDN} = \frac{a}{4(1-\mu)}, p_1^{DDN} = \frac{a\left[s(2-\mu)+\mu-\frac{2+\mu}{4(1-\mu)}\right]}{4-\mu^2}, p_2^{DDN} = \frac{a\left[\frac{7}{4}+\frac{3}{4(1-\mu)}-s(2-\mu)\right]}{4-\mu^2}$$

$$L^{DDN} = \frac{a^2k\alpha\xi}{8k_1(2-3\mu+\mu^2)(\eta+\rho)}, F_1^{DDN} = \frac{a^2k\xi\beta_1[2-4s(2-\mu)-3\mu]^2}{16k_2(4-\mu^2)^2(\eta+\rho)}, F_2^{DDN} = \frac{a^2k\xi\beta_2[-6+4s(2-\mu)+\mu]^2}{16k_3(4-\mu^2)^2(\eta+\rho)}$$

(2) Optimal trajectory of the fresh quality goodwill:

$$G^{DDN}(t) = (G_0 - G_\infty^{DDN})e^{-\rho t} + G_\infty^{DDN}$$

Where, $G_\infty^{DDN} = \frac{a^2k\xi^2}{16\eta(\eta+\rho)}\left\{\frac{2\alpha^2}{k_1(2-3\mu+\mu^2)} + \frac{k_3\beta_1^2[2-4s(2-\mu)-3\mu]^2 + k_2\beta_2^2[-6+4s(2-\mu)+\mu]^2}{k_2k_3(4-\mu^2)^2}\right\}$

(3) Profit of the manufacturer, retailer 1 and retailer 2:

$V_M^{DDN}(G) = A_1G + A_2; V_{R_1}^{DDN}(G) = A_3G + A_4; V_{R_2}^{DDN}(G) = A_5G + A_6$

Where, $A_1 = \frac{1}{8\rho}\left(\frac{a^2k}{2-3\mu+\mu^2} - 8\eta A_1\right)$, $A_2 = \frac{1}{2\rho}\xi^2A_1\left(\frac{\alpha^2}{k_1}A_1 + \frac{2\beta_1^2}{k_2}A_3 + \frac{2\beta_2^2}{k_3}A_5\right)$

$A_3 = \frac{1}{16\rho}\left(\frac{a^2k(2+4s(-2+\mu)-3\mu)^2}{(-4+\mu^2)^2} - 16\eta A_3\right)$, $A_4 = \frac{1}{2\rho}\xi^2A_3\left(\frac{2\alpha^2}{k_1}A_1 + \frac{\beta_1^2}{k_2}A_3 + \frac{2\beta_2^2}{k_3}A_5\right)$

$A_5 = \frac{1}{16\rho}\left(\frac{a^2k(-6-4s(-2+\mu)+\mu)^2}{(-4+\mu^2)^2} - 16\eta A_5\right)$, $A_6 = \frac{1}{2\rho}\xi^2A_5\left(\frac{2\alpha^2}{k_1}A_1 + \frac{2\beta_1^2}{k_2}A_3 + \frac{\beta_2^2}{k_3}A_5\right)$

(4) Total profit of fresh supply chain: $V^{DDN} = V_M^{DDN} + V_{R_1}^{DDN} + V_{R_2}^{DDN}$.

Proposition 1. Under the double decentralised strategy without blockchain, the impact of consumers' preference for fresh products from Retailer 1 (s) and competitive advantage coefficient of two retailers (μ) on the optimal pricing of fresh suppliers (ω) and retailers (p_1, p_2), manufacturer's freshness-keeping technology level (L) and retailer's carbon abatement technology level (F_1, F_2), are summarised in the tables.

Table 1. Sensitivity analysis in the Model-DDN

	ω^{DDN}	p_1^{DDN}	p_2^{DDN}	L^{DDN}	F_1^{DDN}	F_2^{DDN}
s	—	↗	↘	—	↘↗ (if $\mu < \frac{2}{3}$) ↘ (if $\mu > \frac{2}{3}$)	↘↗ (if $\mu < \frac{2}{3}$) ↗ (if $\mu > \frac{2}{3}$)
μ	↗	↗	↗	↗	↗	↗

Source: Authors' own creation.

II Double Centralised Strategy (Model-CCN)

In the double centralised strategy, the fresh manufacture will vertically integrate with retailer 1 and retailer 2 simultaneously to form the alliance. The manufacturer and retailers jointly determine the freshness-keeping technology L^{CCN}, carbon abatement technology $F_i^{CCN}(i = 1, 2)$ and retail price $p_i^{CCN}(i = 1, 2)$ to achieve maximum benefits in the fresh supply chain.

Theorem 2. In the double centralised strategy without blockchain, the optimal strategies of the manufacturer and competitive retailers in the fresh supply chain are as follows.

(1) Optimal decisions of fresh supply chain:

$$p_1^{CCN} = \frac{a[s+\mu(1-s)]}{2(1-\mu^2)},\ p_2^{CCN} = \frac{a[1-s(1-\mu)]}{2(1-\mu^2)}, L^{CCN} = \frac{a^2k\xi\alpha[1-2(1-s)s(1-\mu)]}{4k_1(1-\mu^2)(\eta+\rho)},$$

$F_1^{CCN} = \frac{a^2 k\xi\beta_1[1-2(1-s)s(1-\mu)]}{4k_2(1-\mu^2)(\eta+\rho)}$, $F_2^{CCN} = \frac{a^2 k\xi\beta_2[1-2(1-s)s(1-\mu)]}{4k_3(1-\mu^2)(\eta+\rho)}$

(2) Optimal trajectory of the fresh quality goodwill:

$$G^{CCN}(t) = (G_0 - G_\infty^{CCN})e^{-\rho t} + G_\infty^{CCN}$$

where $G_\infty^{CCN} = \frac{a^2 k\xi^2[1-2(1-s)s(1-\mu)][k_1k_3\beta_1^2+k_2(k_3\alpha^2+k_1\beta_2^2)]}{-4\eta k_1k_2k_3(1-\mu^2)(\eta+\rho)}$.

(3) Overall profit of the fresh supply chain: $V^{CCN}(G) = Z_1G + Z_2$

Where, $Z_1 = \frac{a^2k(-1+2(-1+s)s(-1+\mu))}{4(-1+\mu^2)(\eta+\rho)}$, $Z_2 = \frac{a^4k^2(1-2(-1+s)s(-1+\mu))^2\xi^2(k_1k_3\beta_1^2+k_2(\alpha^2k_3+k_1\beta_2^2))}{32(-1+\mu^2)^2\rho(\eta+\rho)^2k_1k_2k_3}$.

Proposition 2. In the double centralised strategy without Blockchain, the impact of the competitive advantage coefficient for two retailers (μ) and probability of purchasing fresh products from retailer 1 (s) on the manufacturer' freshness-keeping technology level (L), retailer's carbon abatement level (F_1, F_2) and retail prices (p_1, p_2) are:

(1) $\frac{\partial p_1^{CCN}}{\partial\mu}, \frac{\partial p_2^{CCN}}{\partial\mu} > 0$; $\frac{\partial L^{CCN}}{\partial\mu}, \frac{\partial F_1^{CCN}}{\partial\mu}, \frac{\partial F_2^{CCN}}{\partial\mu} > 0$.

(2) $\frac{\partial p_1^{CCN}}{\partial s} > 0$, $\frac{\partial p_2^{CCN}}{\partial s} < 0$; When $s < \frac{1}{2}, \frac{\partial F_1^{CCN}}{\partial s} < 0$;

when $s = \frac{1}{2}, \frac{\partial F_1^{CCN}}{\partial s} = 0$; when $s > \frac{1}{2}, \frac{\partial F_1^{CCN}}{\partial s} > 0$.

(3) $F_1^{CCN} = \frac{k_1\beta_1}{k_2\alpha}L^{CCN}$, $F_2^{CCN} = \frac{k_1\beta_2}{k_3\alpha}L^{CCN}$.

Proposition 2 indicates that the optimal retail price of two fresh retailers and the manufacturer's freshness-keeping technology and retailers' carbon abatement level are positively correlated with the competitive advantage coefficient of themselves. This means that retailers with a higher competitive advantage could expect to set a higher retail price for economic benefits. And the higher competitive advantage coefficient of two retailers will accelerate the technology upgrade in the fresh supply chain. Moreover, the optimal retail price for retailer 1 is positively correlated with the probability of consumers' purchasing fresh products from retailer 1. While that for retailer 2 is the opposite, indicating the negative effect, and the optimal technical investments of the manufacturer and retailers are in a fixed proportion relationship.

Therefore, when considering the enhancement of carbon abatement level and freshness-keeping technology, the fresh supply chain should not indiscriminately increase the investment. Instead, it should select the inputs in a reasonable proportion to achieve the optimal decision-making goal. This approach ensures that the supply chain can optimise its resource allocation while maintaining a balance between improving technology, controlling prices, and maximising profits.

III Mixed Strategy 1 (Model-CDN)

Under mixed strategy 1, the fresh manufacture will only vertically integrate with retailer 1 to form the alliance. Firstly, the vertical alliance determines the freshness-keeping technology L^{CDN}, the carbon abatement level F_1^{CDN}, wholesale price ω^{CDN} and retail price ${p_1}^{CDN}$ to maximise their rewards. Next, retailer 2 makes its own optimal decisions independently.

IV Mixed Strategy 2 (Model-DCN)

Under mixed strategy 2, the fresh manufacture will only vertically integrate with retailer 2 to form the alliance. Firstly, the vertical alliance determines the freshness-keeping technology L^{DCN}, the carbon abatement level F_2^{DCN}, wholesale price ω^{DCN} and retail price ${p_1}^{DCN}$ to maximise their rewards. Next, retailer 1 makes its own optimal decisions independently.

Table 2. The equilibrium results under decision models

	Mixed Strategy 1	*Mixed Strategy 2*
ω	$\frac{a[1-s(1-\mu)]}{2(1-\mu^2)}$	$\frac{a[s+\mu(1-s)]}{2(1-\mu^2)}$
p_1	$\frac{a[s+\mu(1-s)]}{2(1-\mu^2)}$	$\frac{a[2\mu+s(1-\mu)(3+\mu)]}{4(1-\mu^2)}$
p_2	$\frac{a[3-\mu^2-s(1-\mu)(3+\mu)]}{4(1-\mu^2)}$	$\frac{a[1-s(1-\mu)]}{2(1-\mu^2)}$
L	$\frac{a^2k\xi\alpha[1+s^2(3-\mu)(1-\mu)-2s(1-\mu)^2+\mu^2]}{8k_1(1-\mu^2)(\eta+\rho)}$	$\frac{a^2k\xi\alpha[2-s(1-\mu)[4-s(3-\mu)]]}{8k_1(1-\mu^2)(\eta+\rho)}$
F_1	$\frac{a^2k\xi\beta_1[1+s^2(3-\mu)(1-\mu)-2s(1-\mu)^2+\mu^2]}{8(1-\mu^2)(\eta+\rho)k_2}$	$\frac{a^2ks^2\xi\beta_1}{16k_2(\eta+\rho)}$
F_2	$\frac{a^2k\xi\beta_2(1-s)^2}{16k_3(\eta+\rho)}$	$\frac{a^2k\xi\beta_2[2-s(1-\mu)[4-s(3-\mu)]]}{8k_3(1-\mu^2)(\eta+\rho)}$
π	$(W_1+W_3)G+(W_2+W_4)$	$(H_1+H_3)G+(H_2+H_4)$

Source: Authors' own creation.

3.3.2 Extended Model with Blockchain technology

The coordination strategy of fresh supply chain after the blockchain adoption in the long-run is studied in this part. When blockchain is implemented, the fixed deployment cost is required from the manufacturer. The unit cost of blockchain label management for each fresh product is transferred to two competitive retailers as blockchain usage cost, which we still regard as unit cost of blockchain implementation in the whole paper. Therefore, four models under different vertical integration strategies after blockchain implementation are developed. The profit function of the manufacturer and the two retailers in the fresh supply chain is as follows:

$$\begin{cases} {\pi_M}^Y = \omega^Y\left({D_1}^Y+{D_2}^Y\right)kG-{C_M}^Y-C_B \\ {\pi_{R_1}}^Y = ({p_1}^Y-\omega^Y-c){D_1}^YkG-{C_{R_1}}^Y \\ {\pi_{R_2}}^Y = ({p_2}^Y-\omega^Y-c){D_2}^YkG-{C_{R_2}}^Y \end{cases} \tag{7}$$

The four vertical integration models are, respectively, Model-DDY, Model-CDY, Model-DCY and Model-CCY, similar to the case without the introduction of blockchain technology, we can calculate by Equations (7) to find the equilibrium solution of the four models.

Proposition 3. Under four vertical integration strategies with blockchain, we could obtain the following:

(1) $\frac{\partial \omega}{\partial c} < 0$; (2) $\frac{\partial p_1}{\partial c} > 0, \frac{\partial p_2}{\partial c} > 0$.

Under four vertical integration strategies with blockchain, the higher unit cost of blockchain implementation increases the retail prices of two retailers, while decreasing the wholesale price of the manufacture. It indicates that retailers will raise the retail price to offset the extra expense of blockchain implementation, and the manufacturer will choose to lower the wholesale price for the retailer who does not join the alliance. It might be that the alliance obtains sufficient benefits from the blockchain implementation, and the manufacturer is willing to reduce the wholesale price to help the retailer who does not join the alliance sell more products with blockchain technology.

4. Comparative analysis

Based on the General and Extended Model, we perform a detailed comparison of the optimal wholesale price (ω), retail prices (p_1, p_2), freshness-keeping technology (L) and carbon abatement technology (F_1, F_2) across four vertical integration strategies. Additionally, the interaction between the vertical integration strategy and the optimal decision with the implementation of a blockchain platform is also examined.

Proposition 4. For the double-decentralised strategy, the comparison of optimal pricing and technology level without and with blockchain implementation is listed below.

(1) *Manufacturer's wholesale price* (ω)*:* $\omega^{DDY} < \omega^{DDN}$

(2) *Retail price* (p_1, p_2)*:*

① *Retailer 1's retail price:* $p_1^{DDY} > p_1^{DDN}$*;*

② *Retailer 2's retail price:* $p_2^{DDY} > p_2^{DDN}$*.*

(3) *Manufacturer's freshness-keeping technology* (L)*:*

① *If* $c \in (c_1, c_2)$, $L^{DDY} > L^{DDN}$*;*

② *If* $c \notin (c_1, c_2)$, $L^{DDY} < L^{DDN}$*.*

where $c_1 = \frac{a(1-\sqrt{\xi})}{2(1-\mu)}, c_2 = \frac{a(1+\sqrt{\xi})}{2(1-\mu)}$.

(4) *Retailers' carbon abatement technology* (F_1, F_2)*:*

① *If* $c_{\Delta 1} < c < c_{\Delta 2}$, *we have* $F_1^{DDY} > F_1^{DDN}$*; else* $F_1^{DDY} < F_1^{DDN}$*.*

where $c_{\Delta 1} = \frac{a[3\mu+4s(2-\mu)-2](1-\sqrt{\xi})}{2(2-\mu-\mu^2)}$, $c_{\Delta 2} = \frac{a[3\mu+4s(2-\mu)-2](1+\sqrt{\xi})}{2(2-\mu-\mu^2)}$

② *If* $c_{\Delta 3} < c < c_{\Delta 4}$, *we have* $F_2^{DDY} > F_2^{DDN}$*; else* $F_2^{DDY} < F_2^{DDN}$*.*

where $c_{\Delta 3} = \frac{a[-\mu-4s(2-\mu)+6](1-\sqrt{\xi})}{2(2-\mu-\mu^2)}$, $c_{\Delta 4} = \frac{a[-\mu-4s(2-\mu)+6](1+\sqrt{\xi})}{2(2-\mu-\mu^2)}$

The model indicates the manufacturer and retailers will adjust their pricing strategy after blockchain implementation in fresh supply chain. In order to incentivise retailers to embrace the blockchain, the manufacturer attracts retailers by offering lower wholesale price. This adjustment is due to retailers' extra cost of using blockchain, which may create a barrier for retailers' wholesale decision. To recoup the blockchain usage cost and maintain profitability, retailers raise their retail prices to a certain extent. By applying the blockchain, retailers can provide greater transparency and trust in their fresh products, which enhances the perceived value and quality for customers.

Furthermore, the manufacturer's freshness-keeping technology and retailers' carbon abatement technology level is influenced by the unit cost of blockchain implementation. Specifically, when the unit cost falls within certain thresholds, the blockchain implementation could lead to an increase in the investment of freshness-keeping technology and carbon abatement technology. However, when the unit cost is beyond the thresholds, the effect will be counterproductive. Too high or too low of it will discourage the investment in technology promotion.

As $c_2 - c_1 = \frac{a\sqrt{\xi}}{1-\mu}$, $c_{\Delta 2} - c_{\Delta 1} = \frac{a\sqrt{\xi}[3\mu+4s(2-\mu)-2]}{2-\mu-\mu^2}$, $c_{\Delta 4} - c_{\Delta 3} = \frac{a\sqrt{\xi}[-\mu-4s(2-\mu)+6]}{2-\mu-\mu^2}$, it means larger market size and higher proportion consumers could perceive for fresh quality will contribute to the manufacturer' freshness-keeping technology promotion after blockchain implementation. We need also notice that $c_{\Delta 1}$ and $c_{\Delta 2}$ is positive only if consumers' preference for retailer 1 is high enough (i.e., $s > \frac{2-3\mu}{4(2-\mu)}$). The above suggests the unit cost of blockchain usage for retailers directly impacts technology level in the fresh supply chain.

Proposition 5. Under the double-centralised strategy without and with blockchain, the impact of manufacturer's fixed cost of blockchain implementation (C_B) on the total profit of the fresh supply chain satisfy:

(1) $\pi^{CCY} > \pi^{CCN}$, *if* $C_B \in (0, \Delta C_{B1})$;

(2) $\pi^{CCY} < \pi^{CCN}$, *if* $C_B \in (\Delta C_{B1}, +\infty)$, .

where
$$\Delta C_{B1} = \frac{k^2(\eta+2\rho)\left(\frac{1}{k_1}\alpha^2 + \frac{1}{k_2}\beta_1^2 + \frac{1}{k_3}\beta_2^2 - \xi_N\right)}{32\eta(\eta+\rho)^2}\left\{\left((2c^2(1-\mu)+2ac) + \frac{a^2(1-2(1-s)s(1-\mu))}{1-\mu^2}\right)^2 + \left(\frac{2a^2(1-s)s\xi_N}{1+\mu}\right)^2\right\}.$$

The alliance will be less willing to adopt the blockchain if the fixed deployment cost is high. Specifically, when the cost coefficient of freshness-keeping technology and carbon abatement technology is high, firms will be prevented to advance the technology, resulting in lower fresh quality. Moreover, if the natural decay rate of fresh quality goodwill is large, then it will be difficult to maintain fresh quality. Blockchain technology will aggravate the inferior fresh quality image following the above concerns. There are many decisive factors influencing the blockchain implementation, such as size of the fresh market, unit cost of blockchain implementation, the influence coefficient of consumers' perceived fresh quality on the fresh quality goodwill, and the influence coefficient of the fresh quality goodwill on market demand. Larger indexes will encourage and stimulate the deployment of the blockchain technology. Therefore, the fresh supply chain should also accurately identify the optimal strategy for introducing blockchain to bring greater economic benefits.

Proposition 6. For the double-decentralised strategy, the impact of the fixed cost of blockchain implementation (C_B) on manufacturer's profit satisfies

(1) If $C_B \in (0, \Delta C_{B2})$, $\pi_M^{DDY} > \pi_M^{DDN}$;

(2) If $C_B \in (\Delta C_{B2}, +\infty)$, $\pi_M^{DDY} < \pi_M^{DDN}$.

where $\Delta C_{B2} = \frac{\alpha^2 k^2 [a^4 \xi^2 - (a + 2c(1-\mu))^4]}{128 k_1 (2-\mu)^2 (1-\mu)^2 (\eta+\rho)^2}$.

As we could see, only if the fixed cost is small enough, the profit of the manufacturer will increase with blockchain. The threshold is positively affected by market demand relevant factors ($\alpha \to \lambda \to k$), while negatively affected by cost-profit factors ($k_1 \to \eta \to \rho$). More specifically, the factors of freshness-keeping technology on market demand will raise the threshold, while the factors of this technology on long-term profit will reduce the threshold.

Proposition 7. Without and with the blockchain implementation, the magnitude of the total profit under four vertical integration strategies in the fresh supply chain remains the same order: $\pi^{CC\Lambda} > \pi^{DC\Lambda} > \pi^{CD\Lambda} > \pi^{DD\Lambda}$, $\Lambda \in \{N, Y\}$.

The total profit of the competitive fresh supply chain is the highest under the double centralised strategy and the lowest under the double decentralised model. The case of mixed strategy is in between. That is to say, the manufacturer chooses to vertically integrated with retailers could significantly enhance the benefits for the fresh supply chain management regardless of whether blockchain technology is used or not.

5. Numerical Simulation

Numerical simulation is conducted to further verify the propositions in this paper via MATLAB. This method could intuitively demonstrate the impact of retailers' competitive advantage and consumers' preference for retailers on optimal pricing and technology level and overall profit in fresh supply chain under different vertical integration strategies before and after blockchain implementation. The parameter settings are listed below: $k_1 = 0.1$, $k_2 = 0.1$, $k_3 = 0.1$, $\alpha = 0.6$, $\beta_1 = 0.4$, $\beta_2 = 0.4$, $\xi_N = 0.6$, $\eta = 0.2$, $k = 0.5$, $a = 1, s = 0.6$, $C_B = 0.1$, $\rho = 0.3$. In order to ensure the feasibility of the optimal strategy in each model, we first set retailers' unit cost of blockchain implementation as $c = 0.05$ and measure the impact of retailers' competitive advantage on manufacturer's wholesale price. The horizontal axis is set within [0, 0.5].

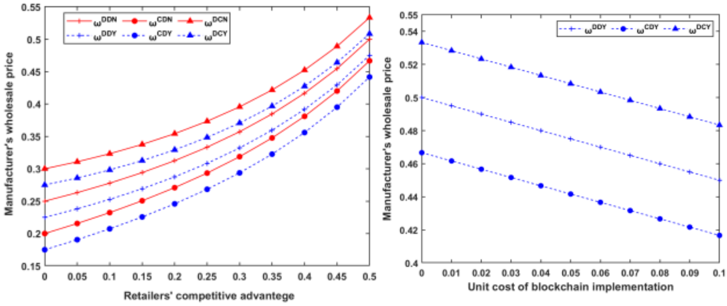

Figure 3. μ and c on wholesale price (ω)
Source: Authors' own creation.

Figure 3 indicates that before and after blockchain implementation, the wholesale price is positively correlated with retailers' competitive advantage, and the adoption of blockchain in the fresh supply chain can effectively reduce the manufacturer's wholesale price, which is consistent with Proposition 1 and 3. And if retailers' unit cost of blockchain implementation is higher, the manufacturer tends to reduce its wholesale price slightly to compensate the retailer. This practice also encourages the procurement after building of the blockchain, thereby maintaining the stability of its own earnings.

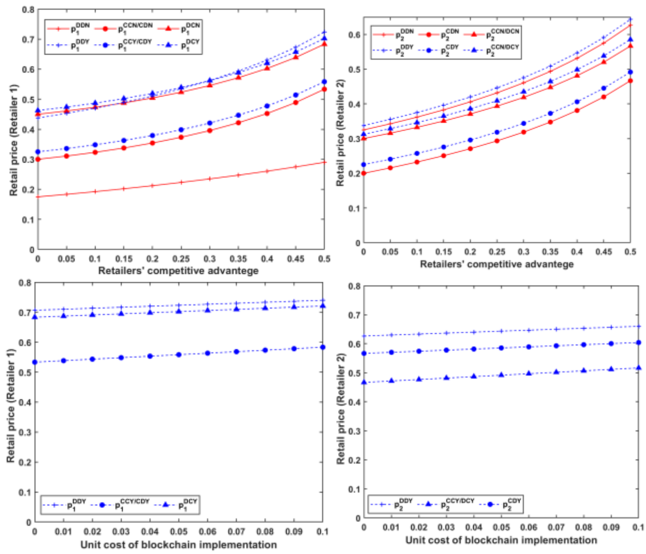

Figure 4. μ and c on retail price (p_1, p_2)
Source: Authors' own creation.

Figure 4 indicates that the retail price for each retailer increases with competitive advantage. Furthermore, retailer 1 has the same retail price in Model-CC and Model-CD, and retailer 2 has the same retail price in Model-CC and Model-DC before and after blockchain implementation. And the retail price of both retailers is the highest in Model-DD, which indicates that the decentralised vertical integration strategy is not conducive to retailers ' sales of products. Excessive retail prices will lead to lower market demand and thus damage the profits of the supply chain.

At the same time, the retail price for each retailer increases with the unit cost of blockchain implementation, which is consistent with Proposition 3. which indicates that the higher the cost paid by the retailer to apply the quality disclosure function of the blockchain, the retailer can only achieve stable returns by increasing its retail price. Therefore, the cost of adopting the blockchain in the fresh supply chain should be set within a certain threshold to avoid damaging the development of the supply chain.

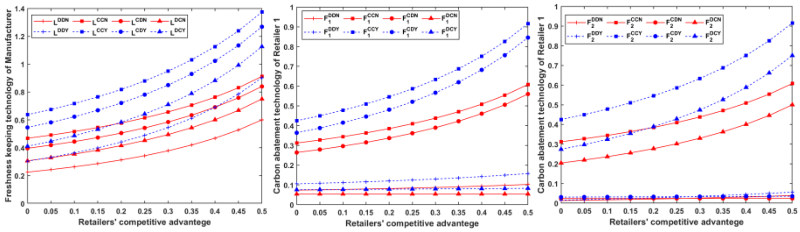

Figure 5. μ on freshness-keeping technology (L) and carbon abatement technology (F_1, F_2)

Source: Authors' own creation.

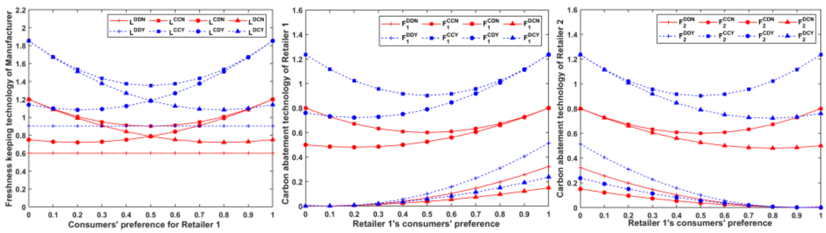

Figure 6. s on freshness-keeping technology (L) and carbon abatement technology (F_1, F_2)

Source: Authors' own creation.

Figure 5 reveals higher competitive advantage will encourage the technology upgrade within the vertical alliance before and after blockchain implementation, while the technology level of the retailer outside the alliance keeps unchanged. Furthermore, from figure 6 we could observe that blockchain implementation chain can significantly enhance the freshness-keeping technology and carbon abatement technology in the fresh supply chain. We also find that the overall technology level in the fresh supply chain is the highest when the manufacture vertically integrated with both two retailers.

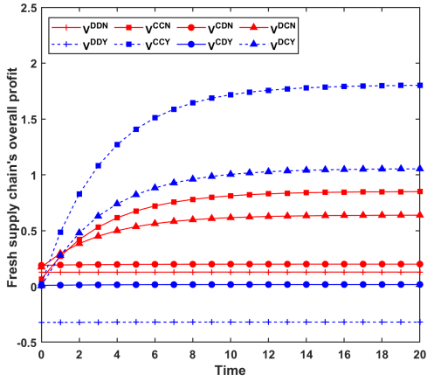

Figure 7. Evolution of fresh supply chain's overall profit $\mathbf{V(t)}$
Source: Authors' own creation.

Before and after blockchain implementation, from figure 7 we observe that the magnitude of the total profit under four vertical integration strategies in the fresh supply chain remains of the same order. The profit is the highest when manufacture form vertical alliance with both two retailers, while lowest when there exists no vertical integration. This is consistent with Proposition 8. Retailers do not adopt a decentralised vertical integration strategy, the overall profit of the fresh supply chain is always the lowest regardless of whether the blockchain is introduced or not, and because the blockchain platform increases the manufacturer's fixed deployment cost and the retailer's variable use cost, Model-DDY has a negative profit after joining the blockchain, which is very unsatisfactory. When the retailer adopts the dual integration strategy, the fresh supply chain can obtain the highest profit. At this time, building a blockchain platform can still further improve the profit of the fresh supply chain. Therefore, a certain conclusion can be obtained through numerical analysis, which can be effectively applied to the actual operation of the fresh supply chain.

6. Discussion

This article mainly examines the impact of vertical integration strategy on pricing strategy, technological upgrading, and total profit of fresh supply chain under oligopolistic competition, explores the potential performance of blockchain implementation in fresh supply chain. The conclusions are as follows.

(1) Under four vertical integration strategies, our study indicates that retailers' higher competitive advantage will increase the wholesale price and retail prices (except for the double centralised strategy where the wholesale price does not exist). Consumers' higher preference for one retailer will increase the retail price of oneself while decreasing that of the other retailer. Furthermore, consumers' preference for retailers has no influence on the wholesale price.

(2) Once the manufacture vertically integrated with one retailer (focal retailer) more preferred by consumers, they will offer lower wholesale price to the retailer outside the alliance. When there exists vertical alliance, the retail price of the retailer

within the alliance stays unchanged whether the other retailer joins the alliance or not. And the technology level of the retailer outside the vertical alliance increases with consumers' preference on the retailer, while competitive advantage has no effect on the technology level. In addition, the technology level of each firm within the vertical alliance synchronously changes with retailers' competitive advantage and consumers' preference for them.

(3) The higher unit cost of blockchain implementation increases the retail prices for two retailers, while decreasing the wholesale price for the retailer outside the alliance under four vertical integration strategies with blockchain. The total profit of the competitive fresh supply chain is the highest under the double centralised strategy and the lowest under the double decentralised model. This insight highlights the potential benefits of integrating blockchain into supply chain management practices and encourages further exploration of its diverse applications within the industry.

Therefore, Retailers operating within the fresh supply chain must carefully evaluate the competitive advantage and their influence on pricing strategies (consumers' preference). By understanding the mechanism of how these factors affect the wholesale and retail price, retailers can make wiser plans for to optimise their profits while remaining competitive in the market. Managers should consider adopting the double-centralised strategy to form the alliance, ensuring the manufacturer and retailers collaborate closely, as our study reveals this strategy could improve market demand and overall profitability most in the fresh supply chain. They should also prioritise the investments in technologies to realise the fresh quality improvement within the fresh supply chain. While blockchain brings about benefits in terms of quality disclosure and traceability, aligning vertical coordination strategies with the blockchain implementation plan is also necessary. Managers should conduct a thorough evaluation of the supply chain context and the potential benefits of blockchain.

This article acknowledges several limitations and suggests potential avenues for future research. One limitation of this study is the assumption of asymmetric duopoly competition among the retailers. However, competition modes are diverse real practice, and investigating the optimal strategy under other competition modes could further expand the understanding of competitive dynamics and the utilisation of blockchain technology in the fresh supply chain. And blockchain can achieve a wide range of applications and should be further expanded.

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