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Research article

Research on investment optimization and coordination of fresh supply chain considering misreporting behavior under blockchain technology

Xin Yang [a], Mingjing Liu [b], Jinyu Wei [b], Yaoxi Liu [b,*]

[a] *School of Economics and Management, Tianjin Agricultural University, China*
[b] *School of Management, Tianjin University of Technology, China*

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ABSTRACT

In the traditional fresh supply chain, farmers commonly conceal the true quality information of their products in order to achieve better sales. This article focuses on the use of blockchain technology to address the issue of false freshness reporting in a two-level fresh supply chain consisting of a rural cooperative and a supermarket. Taking into account the dual losses of quality and quantity in the process of agricultural products transportation, the impacts of the product freshness and the blockchain investment level on random market demand are quantified in this paper. And game models for centralized and decentralized decision-making before and after investing in blockchain technology are proposed. By comparing the supply chain optimal decisions and performances under different scenarios, a revenue-cost sharing contract is designed to coordinate the decentralized decision-making. Simulation results show that the application of the blockchain technology can further consolidate the superiority of the centralized decision-making. However, there is a certain threshold for the application of the blockchain technology in decentralized decision-making. When the unit cost of blockchain exceeds the threshold, the rural cooperative will abandon its cooperation with the supermarket due to reduced profits. And the combined contract also has a threshold boundary for its coordinating effect on decentralized decision-making.

1. Introduction

Fresh agricultural products as an important part of modern agriculture, its supply chain operation optimization is one of the key issues related to the national economy and people's livelihood. The characteristics of fresh agricultural products are different from those of ordinary normal temperature products, which are perishable and have a short shelf life. This natural attribute also makes agricultural products highly susceptible to quantity and quality losses during long-distance transportation [1]. The decrease in product freshness not only leads to a decrease in consumer demand, but also affects the order volume of retail enterprises. To avoid the short-term impact on order quantity caused by the decrease in product freshness, farms or cooperatives often conceal the true quality information of agricultural products and falsely claim that the products have high freshness. When supermarkets make purchasing and pricing decisions based on this misrepresentation product information, it often results in a decline in performance. This situation,

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* Corresponding author. 391 Binshui West Road, Xiqing District, Tianjin, China.
E-mail address: liu405883443@163.com (Y. Liu).

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where one party in the supply chain obtains critical information that other participants cannot access, leading to inefficient decisions, is referred to as information asymmetry. In fact, based on the causes of information asymmetry, it can be divided into subjective factors leading to information asymmetry and objective factors causing information asymmetry. In fact, based on the differences in the causes of information asymmetry, it can be further subdivided into subjective information asymmetry and objective information asymmetry. The information asymmetry caused by objective factors such as a single information source or delayed data transmission can be solved by expanding information channels or eliminating information silos. However, the information asymmetry caused by subjective reasons such as malicious concealment or false reporting of information cannot be effectively resolved through the above-mentioned methods. This article mainly researches the phenomenon of information asymmetry caused by rural cooperatives falsely reporting on the freshness of agricultural products in the fresh supply chain, which is a subjective information asymmetry. The focus is on analyzing the impact of product information misreporting behavior at upstream nodes on the performances of downstream and the fresh supply chain. The malicious misreporting behavior at the upstream nodes of the fresh supply chain not only exacerbates the information asymmetry of fresh supply chain, but also seriously damages the interests of retail enterprises, ultimately affecting the sustainable development of the entire supply chain. Therefore, it is imperative to conduct research on the malicious misreporting behavior in the fresh supply chain, especially the malicious misreporting on the supply side.

At present, the primary way to address the asymmetric information in the supply chain is to establish a traceable information system. With the continuous development of information technology, blockchain technology, with its characteristics of decentralization, information immutability, and traceability, is being increasingly introduced by more researchers and managers into the information traceability system of fresh supply chain. The integrated application of blockchain and internet of things technology can effectively achieve real-time collection and storage of information at various nodes in the fresh supply chain, ensuring the accuracy of information from the source [2]. The decentralized structure of blockchain helps break down information silos, expand the depth of information sharing, and enhance the symmetrical distribution of information from multiple sources [3]. The consensus mechanism of blockchain technology can permanently record all product information from multiple nodes in the supply chain, which helps to prevent malicious information tampering and concealment [4]. Additionally, the smart contract technology of blockchain can achieve the automatic execution of supply chain transactions by setting automatic triggering mechanisms [5]. While ensuring transaction security, it greatly shortens the transaction time of goods. Saving time is crucial for reducing the transit time of fresh agricultural products and extending their shelf life for sale.

However, the application of blockchain can not only solve malicious misreporting behavior and improve the performance of information traceability system, but also potentially lead to changes in the decision-making environment of the fresh supply chain. In particular, when node enterprises make investment decisions in blockchain, it is important to comprehensively consider and depict the impact of the introduction of blockchain technology on various elements of decision-making. This is also an important prerequisite for the accurate implementation of blockchain investment and a crucial guarantee for the modern and intelligent development of the fresh supply chain.

Taking the above considerations into account, this paper mainly researches the application of the blockchain technology in curbing false reporting behavior in the fresh supply chain, and three main issues are discussed: What kind of changes will the introduction of the blockchain technology bring to the fresh supply chain? Is it more beneficial to all members of the supply chain compared to freshness fraud? If so, does the implementation of this technology have investment boundaries? If not, is there a contractual mechanism that can help promote the adoption of blockchain technology?

Based on the above questions, this article focuses on the fresh supply chain composed of a rural cooperative and a supermarket, and analyzes the impact of asymmetric product quality information on supply chain performance and its solutions. The supermarket aims to curb misreporting of the freshness of agricultural products in the supply chain upstream by investing in a certain level of blockchain technology. The main contributions of this study are as follows: firstly, taking into account the randomness of agricultural product demand, a market demand function is constructed that is jointly influenced by freshness and the level of investment in blockchain technology. And the quality and quantity losses that occur simultaneously during the flow of fresh agricultural products are also taken into account in the model. Secondly, we establish centralized models and decentralized models for scenarios with malicious misreporting behavior and blockchain technology investment, respectively, targeting different decision-making modes. Then, by comparing the changes in supply chain equilibrium solutions before and after investing in blockchain technology, the cost investment threshold and applicable scenarios of blockchain technology under different circumstances are explored. Thirdly, the coordination optimization of the fresh supply chain system is realized through the design of revenue - cost sharing contract.

In the study of the quality information asymmetry problem in the fresh agricultural product supply chain, this paper has obtained several key findings. Firstly, rural cooperatives may hide freshness information for the purpose of increasing short-term order quantity. Such shortsighted behavior can indeed lead to an increase in orders in the early stages. However, in the long run, this strategy may cause serious damage to the stability and trustworthiness of the entire supply chain. Secondly, to maintain the stability and efficiency of the fresh supply chain, choosing the appropriate decision-making mode is crucial. It can be found that the centralized decision-making has a higher advantage regardless of whether or not investing in blockchain technology, and the application of blockchain technology can further enhance this advantage. In addition, the revenue-cost sharing contract designed in this paper can effectively achieve the supply chain coordination, but its application has a certain threshold boundary. When rural cooperatives and supermarkets reach a suitable cost-sharing ratio, blockchain technology can play its greatest synergistic effect.

In summary, this paper starts from a new perspective and systematically explores how concealing the quality information affects the fresh supply chain, as well as the role and value of blockchain technology in it. This not only helps supply chain managers understand and utilize the blockchain technology more deeply, but also clearly points out that for the long-term healthy development of the fresh supply chain, all parties should pay close attention to their revenue-cost sharing ratio, ensure a balance between fairness and efficiency, and thus achieve continuous improvement and optimization of the supply chain.

This article is organized as follows. Section 2 reviews the relevant literature for this study, including information asymmetry in the fresh supply chain, the application of blockchain to the fresh supply chain, and the coordination of fresh supply chain under information asymmetry. Section 3 describes and assumes the basic model. In Section 4, the decision-making model of fresh supply chain under misrepresentation behavior and under the situation of applying blockchain is constructed respectively. Section 5 makes a comparative analysis of the models in the previous chapter. Section 6 establishes a contract coordination model under the background of blockchain technology, and Section 7 provides numerical analysis. Section 8 concludes this research.

2. Literature review

2.1. Exploring information asymmetry in the fresh supply chain

From the perspective of asymmetric information types, researches on information asymmetry in the fresh supply chain mainly involve the asymmetry of cost information and demand information. However, based on the causes of information asymmetry, it can be roughly divided into objective information asymmetry and subjective information asymmetry. Generally, information asymmetry caused by technical problems, differences in upstream and downstream capabilities, fragile information communication channels, and geographical factors in the fresh supply chain is called objective information asymmetry. Liu et al. [6] constructed a two-stage dual-channel fresh agricultural product supply chain model under the condition of demand information asymmetry based on the poor information communication between upstream and downstream of the supply chain. They analyzed the optimal decision-making and the value of information sharing. In the context of information asymmetry caused by factors such as geography, Li et al. [7] proposed a three-level FAP supply chain, analyzing the impact of logistics spatiotemporal costs and FAP freshness on the profits of all stakeholders in the supply chain. Liu and Li [8] designed a two-level supply chain differentiation game model with low-carbon preference and proposed a cost-benefit sharing contract to address the information asymmetry caused by technical limitations. Zhao et al. [9] studied the order decision problem of fresh agricultural product wholesalers under the condition of limited demand information.

Regarding the subjective information asymmetry in the fresh supply chain caused by participants driven by interests, Bin [10] designed three game models for the wholesaler to completely misreporting, partially misreporting, and truthfully announce the purchasing price information, and compared the supply chain performance under the three scenarios. Kang [11] systematically analyzed the impacts of asymmetric information on the freshness of fresh agricultural products on the supply chain when considering risk preferences, and designed a corresponding coordination mechanism. Yan et al. [12] studied the impact of lying about production cost information on the decision-making of other member enterprises and supply chain profits.

Upon comprehensive review, it is evident that the quantitative researches on supply chain information asymmetry mainly focus on the objective factors causing the information asymmetry. There is relatively little research on the deliberate misreporting of freshness of products at the upstream end of the fresh supply chain. In addition, most of the methods used to address the information asymmetry problem focus on establishing an external information traceability system (as detailed in Section 2.2), but ignore the impact of information technology investment on the decision-making environment of the fresh supply chain. There is scarce research on integrating information technology into the quantitative decision-making of the supply chain and addressing subjective deliberate misreporting behavior from the perspective of internal optimization and coordination.

2.2. Application of blockchain in fresh supply chain

As a novel digital technology, blockchain features decentralization, data immutability, and traceability. It can effectively address the lack of trust and high trust costs between nodes in the fresh supply chain, as well as shorten transaction times, improve the overall operational efficiency and responsiveness of the supply chain. As of now, researches on the application of blockchain technology in the fresh supply chain mainly focus on building and improving traceability systems, which is also the primary method and means of addressing information asymmetry in the supply chain. Feng et al. [13] noted that blockchain could serve as a solution to the traceability issues in supply chain management. Gopi et al. [14] conducted feasibility studies on the application of blockchain technology in the supply chains of agricultural products and food, as well as its integration. Wang et al. [15] demonstrated how blockchain technology could overcome obstacles encountered in the tracing process and strengthen trust between supply chain partners. Arena et al. [16] proposed a blockchain-based Internet of Things application, with the platform framework allowing for the tracking of the entire olive oil chain to ensure the traceability of agricultural products.

In addition to studying the improvement of blockchain technology on supply chain traceability systems from a technical perspective, some scholars consider the level of investment in blockchain as an endogenous variable and explore the optimization of blockchain investment in the fresh supply chain environment. Longo et al. [17] used the milk supply chain as an example to analyze the impact of blockchain investment on the food industry through empirical research, and the results indicated that the investment in blockchain by participants in the supply chain is limited. Liu [18] considered the impact of the unreliability of freshness information on market demand and investigated the boundary conditions of the investment in a blockchain-based anti-counterfeiting traceability system in a two-level fresh supply chain. Liu [19] comprehensively considered the impact of blockchain-enabled traceability goodwill and freshness on the demand of fresh product and explored the sales model of e-commerce platforms through quantifying the game process between e-commerce platforms and retailers in four different competitive modes. Established a cost model for supply chains with blockchain technology investments, exploring the limiting factors and investment costs associated with blockchain investment. Qi

[20] researched the deceptive practices in the fresh supply chain involving one manufacturer, one retailer, and a third-party logistics providers. And four scenarios were constructed: 3 PL only misreports preservation service information, 3 PL only misreports logistics cost information, 3 PL misreports both types of information and no misrepresentation by using blockchain technology.

According to the above literature review, researches on the integration of the blockchain and the fresh supply chains are mainly focus on the efficiency improvement of the supply chain traceability system. Only a few scholars have included the level of blockchain investment as an endogenous variable in the joint optimization decision-making of the fresh supply chain. However, most quantitative studies on blockchain investment ignore the dual decay of quality and quantity of fresh products during the flow process, and fails to discuss the improvement of transaction time and quantitative analysis of the application of blockchain in the fresh supply chain.

2.3. *Mechanisms for coordination improvement in asymmetric information of fresh supply chain*

The contract mechanism facilitates cooperation among various parties in the supply chain by providing appropriate incentives and risk allocation, thereby enhancing overall efficiency and responsiveness. Despite extensive research on contracts in the context of ambient temperature product supply chains, such findings cannot be directly applied to the coordination of fresh supply chains. Therefore, in recent years, many scholars have conducted corresponding analyses of coordination contracts for fresh supply chains in different situations, such as revenue sharing [21], cost allocation [22], quantity discounts [23], and so on. Some scholars even address supply chain information asymmetry issues through customizing contracts.

Wu [24] studied supply chain coordination under information asymmetry with a two-part tariff contract and found that such tariffs can coordinate the supply chain and generate positive profits for retailers. Zhou [25] examined supply chain procurement and risk-sharing contract design under stochastic returns and asymmetric productivity information, noting that information asymmetry always disadvantages retailers but benefits manufacturers, though risk-sharing contracts can mitigate the impact of productivity information asymmetry on retailers. Mobini [26] explored the design of multi-period supply chain contracts in a two-level supply chain with information asymmetry, pointing out that when a retailer's choice depends on their private information, the supplier needs to redesign the optimal contract. Ranjbar [27] studied the channel coordination problem in the green supply chain which consists of manufacturers selling green products through retailers under the condition of incorrect information. Pavlov [28] studied how to improve the problem of poor supply chain performance due to incentive inconsistency by designing wholesale price coordination contracts when the source of information asymmetry is private information about fair preferences.

In general, although there is a relatively abundant amount of research on fresh supply chain coordination contract, there is relatively little research on contracts for fresh supply chain in the context of information asymmetry. Moreover, the majority of literature mainly focuses on two single types of contracts: revenue-sharing contract and cost-sharing contract. There is little research discussing the applicable conditions of combination contracts for the promotion and application of blockchain technology in the fresh supply chain, let alone the design of coordination mechanisms in complex environments that comprehensively consider random demand, dual losses, and the shortening of transaction time by blockchain.

3. Problem description and hypothesis

3.1. *Problem description*

The fresh supply chain consists of a large supermarket and a rural cooperative that grows a certain type of fresh produce. The rural cooperative supplies q quantity of fresh agricultural products to the supermarket at the wholesale price of w, and the unit planting cost is c. The supermarket will sell the purchased fresh agricultural products to consumers at the price p, Considering the actual sales situation of fresh produce, the model assumes that the residual value of the product is 0, and the unit processing cost of spoiled agricultural products is s. For the sake of simplicity, the system does not account for loss of reputation due to out-of-stock.

For their own benefit, rural cooperatives often conceal the true information of agricultural products, such as the freshness or the picking time. This behavior of concealing the true quality information of products will have a great impact on the supply chain and seriously consume the benefits of downstream retailers. In order to address the above problem, the supermarket invests in blockchain technology to enhance the transparency and the credibility of the supply chain. On the one hand, with the real-time information tracking and monitoring enabled by blockchain technology, the information asymmetry between upstream and downstream members

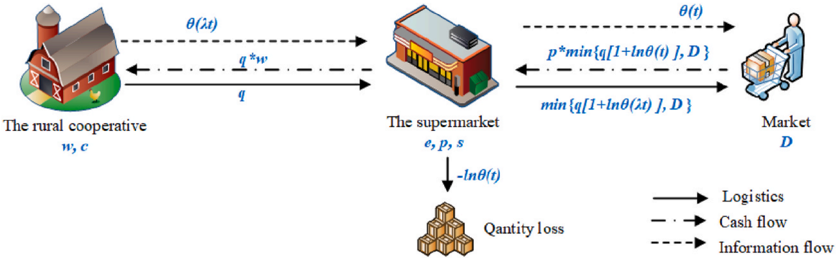

Fig. 1. The fresh supply chain structure under misrepresentation behavior.

in the fresh supply chain can be eliminated. On the other hand, the use of its "smart contract technology" can also accelerate the transaction speed of fresh food.

The structure of the fresh supply chain before and after the application of blockchain technology is shown in Figs. 1 and 2, respectively.

In fact, the investment in blockchain technology is greater and the technology is more refined, the transparency of the fresh supply chain is higher. The downstream of the supply chain can also have a relatively accurate grasp of the freshness of agricultural products, which could increase consumer trust and ultimately enhance market demand. Therefore, the market demand is not only directly affected by the freshness of fresh produce, but also influenced by the investment level of blockchain technology.

3.2. Model assumptions and symbolic implications

The basic assumptions of model construction are as follows:

Assumption 1. There are both quality loss and quantity loss in fresh agricultural products. Among them, quality loss is characterized by the freshness of agricultural products, which is a process of deceleration and decline with time. Similar to Wang and Dan [29], the time function of freshness of agricultural products is $\theta(\mathrm{t}) = \theta^t$, $\theta \in (0,1)$ represents the initial freshness of fresh agricultural products.

Assumption 2. Fresh agricultural products will lose a certain amount in the sales process, and the loss speed is related to the freshness of the product. According to Wang et al. [30], the quantity loss rate is $\varphi(\theta) = -\ln\theta$, $0 < \varphi(\theta) < 1$.

Assumption 3. In the case of asymmetric freshness information, the rural cooperative may engage in false or inaccurate reporting of agricultural products time. According to Chen et al. [31], the actual production time t is misstated as λt. Considering the incentive of lying, the analysis mainly focuses on the case where $\lambda \in [0,1]$. When $\lambda = 0$, the true information of agricultural products is completely concealed. When $\lambda = 1$, the supply chain information is completely transparent.

Assumption 4. Blockchain technology can not only improve the transparency of product information, but also the smart contract technology can speed up the transaction of fresh produce. The transaction time is shortened from the original time t to $\check{t}$ when using blockchain technology. And to ensure the logical validity, let $\lambda t < \check{t}$. According to Yu et al. [32], the investment level of blockchain technology is $c_e = \eta e^2/2$.

Assumption 5. Market demand fluctuates randomly and is affected by both the freshness of agricultural products and the level of blockchain investment, Similar to Yi et al. [33], the market demand function is $D = \theta(t)x$ and the demand under the blockchain technology is $\check{D} = \theta(\check{t})x + \delta e$, where x is the random demand when the freshness is 1. It follows a uniform distribution on $[0,b]$ [34].

For ease of expression, subscript s and r are used to represent the parameters related to the cooperative and the supermarket respectively, and superscripts c, d, o are used to represent centralized decision-making, decentralized decision-making, and the revenue-cost-sharing contract respectively. Other symbols and their meanings are shown in Table 1.

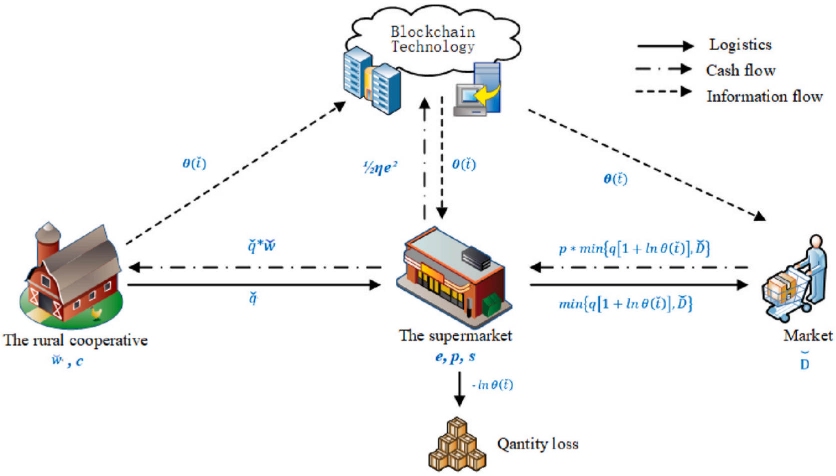

Fig. 2. The fresh supply chain structure after applying blockchain technology.

Table 1
Model symbols and their meanings.

symbol	meaning
π_s, π_r, π	Respectively represents the cooperative profit, the supermarket profit, and the total profit of the fresh supply chain
$\breve{\pi}_s, \breve{\pi}_r, \breve{\pi}$	Respectively represents the revenue of the cooperative, the revenue of the supermarket and the total revenue of the supply chain with blockchain investment
$q, \breve{q}$	Respectively represents the order quantity of the supermarket before and after investing in blockchain
$w, \breve{w}$	Respectively represents the wholesale price before and after investing in blockchain
Δ	Demand sensitivity coefficient for blockchain investment level, $\delta > 0$
Λ	The misrepresentation coefficient, $0 \le \lambda \le 1$
s	Unit deterioration cost
η	Blockchain cost factor, $\eta > 0$
e	The investment level of blockchain
α^{o}, β^{o}	Revenue sharing -cost sharing coefficient, $\alpha^{o}, \beta^{o} \epsilon (0, 1)$

4. Model building and solving

4.1. Fresh supply chain decision model with misrepresentation behavior

4.1.1. Centralized decision making

Centralized decision-making is based on the integration of upstream and downstream information in the fresh supply chain. Therefore, there is no information misrepresentation or asymmetry in this mode, and all members take the maximization of the fresh supply chain profit as the decision-making objective. In this case, equation (1) represents the profit function of the fresh supply chain:

$$\pi^{c} = p\min\{[1 - \varphi(\Theta)]q^{c}, \mathrm{D}\} - cq^{c} - s\varphi(\Theta)q^{c} \tag{1}$$

Because, $\frac{\partial^2 \pi^c (q^c)}{\partial (q^c)^2} = -\frac{p[1-\varphi(\Theta)]^2}{b\theta(t)} < 0$, π^c is a concave function of q^c, let $\frac{\partial \pi^c}{\partial q^c} = 0$, equation (2) represents the optimal order quantity:

$$q^{c*} = \frac{b\Theta(\mathrm{t})[(1 - \varphi(\Theta))p - c - s\varphi(\Theta)]}{p[1 - \varphi(\Theta)]^2} \tag{2}$$

By substituting equation (2) into equation (1), the total system revenue can be written as equation (3):

$$\pi^{c*} = \frac{b\theta(t)[(1 - \varphi(\Theta))p - c - s\varphi(\Theta)]^2}{2p[1 - \varphi(\Theta)]^2} \tag{3}$$

4.1.2. Decentralized decision making

In the case of decentralized decision-making, the upstream and downstream enterprises of the fresh supply chain make decisions from the perspective of their own benefit optimization. This paper takes the Stackelberg game dominated by the rural cooperative as an example for detailed analysis.

The specific game process is as follows: firstly, the rural cooperative determines the wholesale price of agricultural products; subsequently, the supermarket determines the optimal order quantity according to the market demand reaction function of agricultural products, taking into account the freshness information of the products. In this process, the rural cooperative falsely reported the freshness of agricultural products. At this time, equation (4) represents the profit function of the rural cooperative:

$$\pi_s^{\mathrm{d}} = \left(w^{\mathrm{d}} - c\right)q^{\mathrm{d}} \tag{4}$$

When the supermarket obtains false freshness information, its decision function is as equation (5):

$$\pi_r^{\mathrm{d}} = p\min\left([1 - \varphi(\Theta)]q^{\mathrm{d}}, \Theta(\lambda \mathrm{t})\mathrm{x}\right) - w^{\mathrm{d}}q^{\mathrm{d}} - s\varphi(\Theta)q^{\mathrm{d}} \tag{5}$$

According to backward induction, the response function of the supermarket order quantity when there is a misstatement can be obtained by derivation of equation (5):

$$q^{d*} = \frac{b\Theta(\lambda \mathrm{t})[(1 - \varphi(\Theta))p - w^{\mathrm{d}} - s\varphi(\Theta)]}{p[1 - \varphi(\Theta)]^2} \tag{6}$$

Equation (6) is substituted into Equation (4) to obtain the optimal wholesale price of the rural cooperative:

$$\mathrm{w}^{\mathrm{d}*} = \frac{(1 - \varphi(\Theta))p + c - s\varphi(\Theta)}{2} \tag{7}$$

$$\text{And the optimal order quantity of supermarket is : } q^{d*} = \frac{b\Theta(\lambda \mathrm{t})[(1\text{-}\varphi(\Theta))p\text{-}c\text{-}s\varphi(\Theta)]}{2p[1\text{-}\varphi(\Theta)]^2} \tag{8}$$

It is worth noting that consumers can intuitively perceive the real freshness of agricultural products based on their appearance changes when making actual purchases. Thus, the actual profit of the supermarket is as equation (9):

$$\pi_r^{d^*} = pmin\left([1-\varphi(\theta)]q^d, \theta(t)x\right) - w^d q^d - s\varphi(\theta)q^d = b\theta(\lambda t)\frac{[(1-\varphi(\theta))p - s\varphi(\theta) - c]^2}{8p[1-\varphi(\theta)]^2}\left(2 - \frac{\theta(\lambda t)}{\theta(t)}\right) \tag{9}$$

When Equation (7) and Equation (8) are substituted into Equation (4), the income of the rural cooperative can be obtained as equation (10):

$$\pi_s^{d^*} = \frac{b\theta(\lambda t)[(1-\varphi(\theta))p - s\varphi(\theta) - c]^2}{4p[1-\varphi(\theta)]^2} \tag{10}$$

4.2. *Fresh supply chain decision model applying blockchain*

In order to effectively prevent the rural cooperative from malicious misreporting agricultural products information and better protect end consumers, the supermarket invests in blockchain technology to improve the transparency of the fresh supply chain information. And some investment costs should be borne by the supermarket.

4.2.1. *Centralized decision making*

Equation (11) represents the total profit of the fresh supply chain:

$$\check{\pi}^c = pmin\left([1-\varphi(\theta)]\check{q}^c, \check{D}\right) - c\check{q}^c - s\varphi(\theta)\check{q}^c - \frac{1}{2}\eta(e^c)^2 \tag{11}$$

The first-order partial derivatives of equation (11) with respect to $\check{q}^c$ and e^c are calculated, respectively, and their Hessian matrix is shown in equation (12).

$$\begin{bmatrix} \partial^2\dfrac{\check{\pi}^c}{\partial(\check{q}^c)^2} \partial^2\dfrac{\check{\pi}^c}{\partial\check{q}^c\partial e^c} \partial^2\dfrac{\check{\pi}^c}{\partial e^c\partial\check{q}^c} \partial^2\dfrac{\check{\pi}^c}{\partial(e^c)^2} \end{bmatrix} = \begin{bmatrix} -\dfrac{p[1-\varphi(\theta)]^2}{b\theta(\check{t})} & \dfrac{p\delta[1-\varphi(\theta)]}{b\theta(\check{t})} \\ \dfrac{p\delta[1-\varphi(\theta)]}{b\theta(\check{t})} & -\left(\dfrac{p\delta^2}{b\theta(\check{t})} + \eta\right) \end{bmatrix} \tag{12}$$

When the matrix is negative definite, the profit function has a maximum value. Let $\partial\frac{\check{\pi}^c}{\partial\check{q}^c} = 0, \partial\frac{\check{\pi}^c}{\partial e^c} = 0$, the optimal order quantity and the blockchain investment level can be obtained respectively as equation (13) and equation (14):

$$\check{q}^{c*} = \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]\left[p\delta^2 + \eta b\theta(\check{t})\right]}{[1-\varphi(\theta)]^2 p\eta} \tag{13}$$

$$e^{c*} = \frac{\delta[(1-\varphi(\theta))p - c - s\varphi(\theta)]}{[1-\varphi(\theta)]\eta} \tag{14}$$

They are substituted into Equation (11), and the revenue of the fresh supply chain is obtained as equation (15):

$$\check{\pi}^{c*} = \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\check{t})\right)}{2p\eta[1-\varphi(\theta)]^2} \tag{15}$$

4.2.2. *Decentralized decision-making*

The revenue composition of the rural cooperative did not change after the application of blockchain technology. However, as the capital investment party, the supermarket, in addition to the procurement cost, deterioration treatment cost, but also need to bear the corresponding blockchain investment cost. The profit functions of the fresh supply chain members after investing in blockchain are as equation (16):

$$\check{\pi}_s^d = (\check{w}^d - c)\check{q}^d \tag{16}$$

$$\check{\pi}_r^d = pmin\left([1-\varphi(\theta)]\check{q}^d, \check{D}\right) - \check{w}^d\check{q}^d - s\varphi(\theta)\check{q}^d - \frac{1}{2}\eta\left(e^d\right)^2 \tag{17}$$

Through Equation (17), the Hessian matrix is obtained, and it can be seen that when the matrix is negative definite, $\check{\pi}_r^d$ has a maximum. Therefore, set $\partial\frac{\check{\pi}_r^d}{\partial\check{q}^d} = 0$ and $\partial\frac{\check{\pi}_r^d}{\partial e^d} = 0$ respectively, the optimal order quantity and blockchain investment level under decentralized decision-making can be obtained as equation (18) and equation (19)

$$\check{q}^{d*} = [(1-\varphi(\theta))p - \frac{\check{w}^d - s\varphi(\theta)]\left(p\delta^2 + \eta b\theta(\check{t})\right)}{p\eta[1-\varphi(\theta)]^2} \tag{18}$$

$$e^{d*} = \delta[(1-\varphi(\theta))p - \frac{\check{w}^{d} - s\varphi(\theta)]}{[1-\varphi(\theta)]\eta} \tag{19}$$

They are substituted into Equation (16), the optimal wholesale price of the rural cooperative is shown in equation (20).

$$\check{w}^{d*} = \frac{(1-\varphi(\theta))\mathrm{p} - s\varphi(\theta) + \mathrm{c}}{2} \tag{20}$$

and equation (21) represents the optimal order quantity of supermarket:

$$\check{q}^{d*} = \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]\left[\mathrm{p}\delta^{2} + \eta b\theta\left(\check{\mathrm{t}}\right)\right]}{2[1-\varphi(\theta)]^{2}p\eta} \tag{21}$$

Equation (22) represents The optimal investment level of blockchain technology:

$$e^{d*} = \frac{\delta[(1-\varphi(\theta))p - c - s\varphi(\theta)]}{2[1-\varphi(\theta)]\eta} \tag{22}$$

Then the profit of the rural cooperative is shown in equation (23):

$$\check{\pi}_{s}^{d^{*}} = \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^{2}\left(\mathrm{p}\delta^{2} + \eta b\theta\left(\check{\mathrm{t}}\right)\right)}{4p\eta[1-\varphi(\theta)]^{2}} \tag{23}$$

The profit of the supermarket is shown in equation (24):

$$\check{\pi}_{r}^{d^{*}} = \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^{2}\left(\mathrm{p}\delta^{2} + \eta b\theta\left(\check{\mathrm{t}}\right)\right)}{8p\eta[1-\varphi(\theta)]^{2}} \tag{24}$$

5. The impact of decision-making mode and blockchain on fresh supply chain performance

5.1. Discussion on differences in decision-making modes

Corollary 1. *In terms of profitability in the supply chain, centralized decision-making has significant advantages over decentralized decision-making, regardless of whether or not blockchain technology is invested in.*

Proof. *We take the difference in supply chain profit under different decision-making modes before and after investing in blockchain technology*.

$$\pi^{c*} - \pi_{s}^{d^{*}} - \pi_{r}^{d^{*}} = \frac{\mathrm{b}[(1-\varphi(\theta))\mathrm{p} - \mathrm{c} - \mathrm{s}\varphi(\theta)]^{2}}{2\mathrm{p}[1-\varphi(\theta)]^{2}} \cdot \frac{[2\theta(\mathrm{t}) - \theta(\lambda\mathrm{t})]^{2}}{4\theta(\mathrm{t})}$$

$$\check{\pi}^{c*} - \check{\pi}_{s}^{d^{*}} - \check{\pi}_{r}^{d^{*}} = \frac{[(1-\varphi(\theta))\mathrm{p} - \mathrm{c} - \mathrm{s}\varphi(\theta)]^{2}\left(\mathrm{p}\delta^{2} + \eta\mathrm{b}\theta\left(\check{\mathrm{t}}\right)\right)}{8\mathrm{p}\eta[1-\varphi(\theta)]^{2}}$$

According to the economic significance that enterprise profit is always greater than zero, it can be inferred that $(1-\varphi(\theta))\mathrm{p} - \mathrm{c} - \mathrm{s}\varphi(\theta) > 0$. And from hypothesis 2, it can be concluded that $1-\varphi(\theta) > 0$. Then the differences in supply chain profits between centralized and decentralized decision-making before and after investing in blockchain technology are $\pi^{c*} - \pi_{s}^{d^{*}} - \pi_{r}^{d^{*}} > 0, \check{\pi}^{c*} - \check{\pi}_{s}^{d^{*}} - \check{\pi}_{r}^{d^{*}} > 0$.

Obviously, both before and after investing in blockchain technology, the fresh supply chain profit generated by the centralized decision-making is always higher than those generated by decentralized decision-making. And Corollary 1 is proved.

5.2. Centralized decision-making before and after investing in blockchain technology

Corollary 2. *Under the centralized decision, there is always* $\check{q}^{c*} > q^{c*}$、 $\check{\pi}^{c*} > \pi^{c*}$, *and the investment condition of blockchain technology is*:

$$c_{e} = \frac{\delta^{2}[(1-\varphi(\theta))p - c - s\varphi(\theta)]^{2}}{\left[2\eta[1-\varphi(\theta)]^{2}\right]} > 0$$

Proof. The optimal order quantity and supply chain profit before and after investing in blockchain technology under centralized decision-making can be determined by taking the difference. Then we can obtain:

$$\check{q}^{c*}-q^{c*}=\frac{[(1-\varphi(\theta))p-c-s\varphi(\theta)]\left[p\delta^2+\eta b\left(\theta\left(\check{t}\right)-\theta(t)\right)\right]}{p\eta[1-\varphi(\theta)]^2}$$

$$\check{\pi}^{c*}-\pi^{c*}=\frac{[(1-\varphi(\theta))p-c-s\varphi(\theta)]^2\left[p\delta^2+\eta b\left(\theta\left(\check{t}\right)-\theta(t)\right)\right]}{2p\eta[1-\varphi(\theta)]^2}$$

According to assumption 4, it can be concluded that $\theta(\check{t})>\theta(t)$. Then, $\check{q}^{c*}>q^{c*}$, $\check{\pi}^{c*}>\pi^{c*}$. It can be seen that investment in blockchain technology can improve the performance of fresh supply chain systems. According to $c_e=\frac{1}{2}\eta e^2$, the optimal investment level of blockchain technology under centralized decision making is $e^{c*}=\frac{\delta[(1-\varphi(\theta))p-c-s\varphi(\theta)]}{[1-\varphi(\theta)]\eta}$. Under centralized decision making, the investment conditions of blockchain technology is.

$$c_e=\delta^2[(1-\varphi(\theta))p-c-s\varphi(\theta)]^2\Big/\left[2\eta[1-\varphi(\theta)]^2\right]>0$$

5.3. *Decentralized decision-making before and after investment in blockchain technology*

Corollary 3. The relationship between $\check{q}^{d^*}$ and q^{d^*} and between $\check{\pi}_s^{d^*}$ and $\pi_s^{d^*}$ is determined by the relation η_1.When the relation $\eta_1=p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$ and $0<\lambda<0.5$ are satisfied, $\check{q}^{d^*}=q^{d^*}$, $\check{\pi}_s^{d^*}=\pi_s^{d^*}$. When $\eta<\eta_1$, $\check{q}^{d^*}>q^{d^*}$, $\check{\pi}_s^{d^*}>\pi_s^{d^*}$. When $\eta>\eta_1$, $\check{q}^{d^*}<q^{d^*}$, $\check{\pi}_s^{d^*}<\pi_s^{d^*}$.

Proof. make $\sigma_q^d=\frac{\check{q}^{d^*}}{q^{d^*}}$, $\sigma_{\pi_s}^d=\frac{\check{\pi}_s^{d^*}}{\pi_s^{d^*}}$, then, $\sigma_q^d=\frac{\frac{[(1-\varphi(\theta))p-c-s\varphi(\theta)][p\delta^2+\eta b\theta(\check{t})]}{2p\eta[1-\varphi(\theta)]^2}}{\frac{b\theta(\lambda t)[[1-\varphi(\theta)]p-s\varphi(\theta)-c]}{2p[1-\varphi(\theta)]^2}}=\frac{p\delta^2+\eta b\theta(\check{t})}{\eta b\theta(\lambda t)}$, It can be concluded that $\sigma_q^d=\sigma_{\pi_s}^d$.

Let $\sigma_q^d=\sigma_{\pi_s}^d=1$, it can be concluded that $\eta=p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$. And let $\eta_1=p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$. From the constraint conditions $\eta>0$ and $\theta(\lambda t)>\theta(\check{t})$, it can be inferred that when $0<\lambda<0.5$, $\eta_1>0$. The other results are shown in Table 2.

Corollary 4. Under the decentralized decision, there is always $\check{\pi}_r^{d^*}>\pi_r^{d^*}$, and the investment condition of blockchain technology is

$$c_e>b\left(\theta(\lambda t)-\theta\left(\check{t}\right)\right)[(1-\varphi(\theta))p-c-s\varphi(\theta)]^2\Big/\left[8p(1-\varphi(\theta))^2\right]$$

Proof. suppose $\sigma_{\pi_r}^d=\frac{\check{\pi}_r^{d^*}}{\pi_r^{d^*}}$, then $\sigma_{\pi_r}^d=\frac{\frac{[(1-\varphi(\theta))p-c-s\varphi(\theta)]^2(p\delta^2+\eta b\theta(\check{t}))}{8p\eta[1-\varphi(\theta)]^2}}{\frac{b\theta(\lambda t)[(1-\varphi(\theta))p-s\varphi(\theta)-c]^2}{8p[1-\varphi(\theta)]^2}\left(2-\frac{\theta(\lambda t)}{\theta(t)}\right)}=\frac{\theta(t)(p\delta^2+\eta b\theta(\check{t}))}{\eta b\theta(\lambda t)(2\theta(t)-\theta(\lambda t))}$, let, $\sigma_{\pi_r}^d=1$, It can be obtained

$\eta_2=\theta(t)p\delta^2/[b(2\theta(t)\theta(\lambda t)-\theta(t)\theta(\check{t})-(\theta(\lambda t))^2)]$, because $(2\theta(t)\theta(\lambda t)-\theta(t)\theta(\check{t})-(\theta(\lambda t))^2)<0$, then, $\eta_2<0$, that is, $\eta>\eta_2$, $\check{\pi}_r^{d^*}>\pi_r^{d^*}$.

When $\eta<\eta_1$, $\check{q}^{d^*}>q^{d^*}$ and $\check{\pi}_s^{d^*}>\pi_s^{d^*}$.When $\eta>\eta_2$, $\check{\pi}_r^{d^*}>\pi_r^{d^*}$.Therefore, when $\eta<\eta_1$, there are benefits to investing in blockchain technology supply chain members. The optimal investment level of blockchain technology under decentralized decision-making is $e^{d^*}=\frac{\delta[(1-\varphi(\theta))p-c-s\varphi(\theta)]}{2[1-\varphi(\theta)]\eta}$, the blockchain cost impact coefficient is $\eta<p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$. Therefore, the condition for investing in blockchain under decentralized decision making is $c_e>b(\theta(\lambda t)-\theta(\check{t}))[(1-\varphi(\theta))p-c-s\varphi(\theta)]^2/[8p(1-\varphi(\theta))^2]$.

6. Contract coordination in the context of blockchain technology

In order to improve the performance of the fresh supply chain under the scenario of blockchain investment, this paper designs a combined contract of "revenue - cost sharing" for Pareto improvement. The rural cooperative shares the blockchain technology investment cost with the proportion of $1-\alpha^o$. At the same time, the supermarket shares $1-\beta^o$ of its own income with the rural cooperative. Therefore, under the revenge-sharing -cost-sharing contract, the profit functions of the fresh supply chain member are as follows.

Equation (25) represents the profit of the rural cooperative:

$$\check{\pi}_s^o=(\check{w}^o-c)\check{q}^o+(1-\beta^o)pmin\left([1-\varphi(\theta)]\check{q}^o,\check{D}\right)-\frac{1}{2}(1-\alpha^o)\eta(e^o)^2 \tag{25}$$

The supermarket profit function is shown in equation (26):

Table 2
Comparison of retailer order quantity and supplier income under decentralized decision.

Conditions	Conclusion	
$0<\eta<p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$	$\check{q}^{d^*}>q^{d^*}$	$\check{\pi}_s^{d^*}>\pi_s^{d^*}$
$\eta=\eta_1=p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$	$\check{q}^{d^*}=q^{d^*}$	$\check{\pi}_s^{d^*}=\pi_s^{d^*}$
$\eta>p\delta^2/b(\theta(\lambda t)-\theta(\check{t}))$	$\check{q}^{d^*}<q^{d^*}$	$\check{\pi}_s^{d^*}<\pi_s^{d^*}$

$$\breve{\pi}_r^o = \beta^o p min\left([1-\varphi(\theta)]\breve{q}^o, \breve{D}\right) - \breve{w}^o\breve{q}^o - s\varphi(\theta)\breve{q}^o - \frac{1}{2}\alpha^o\eta(e^o)^2 \tag{26}$$

The first-order partial derivatives of Equation (26) with respect to $\check{q}^o$ and e^o are obtained, and the Hessian matrix is shown in equation (27).

$$\begin{bmatrix} \partial^2\frac{\breve{\pi}_r^o}{\partial(\breve{q}^o)^2}\ \partial^2\frac{\breve{\pi}_r^o}{\partial\breve{q}^o\partial e^o}\ \partial^2\frac{\breve{\pi}_r^o}{\partial e^o\partial\breve{q}^o}\ \partial^2\frac{\breve{\pi}_r^o}{\partial(e^o)^2} \end{bmatrix} = \begin{bmatrix} -\frac{\beta^o p[1-\varphi(\theta)]^2}{b\theta(\breve{t})} & \frac{\beta^o p[1-\varphi(\theta)]\delta}{b\theta(\breve{t})} \\ \frac{\beta^o p[1-\varphi(\theta)]\delta}{b\theta(\breve{t})} & -\left(\frac{\beta^o p\delta^2}{b\theta(\breve{t})} + \alpha^o\eta\right) \end{bmatrix} \tag{27}$$

Because the matrix is negative definite, the profit function has a maximum value.

Corollary 5. When $\alpha^o = \beta^o$, and $\breve{w}^{o*} = \alpha^o c + (\alpha^o - 1)s\varphi(\theta)$, the combined contract can reach the level of centralized decision making. When the contract parameter is $(\alpha^o/\beta^o)\epsilon(0.25, 0.5)$, the combined contract can achieve the Pareto optimization of the fresh supply chain.

Proof. Under the coordination state of "revenue - cost sharing contracts. Let $\partial\frac{\breve{\pi}_r^o}{\partial\breve{q}^o} = 0, \partial\frac{\breve{\pi}_r^o}{\partial e^o} = 0$, we can obtain equation (28) and equation (29).

$$\breve{q}^{o*} = [(1-\varphi(\theta))\beta^o p - \frac{\breve{w}^o - s\varphi(\theta)]\left[\beta^o p\delta^2 + \alpha^o\eta b\theta(\breve{t})\right]}{\alpha^o\beta^o\eta p[1-\varphi(\theta)]^2} \tag{28}$$

$$e^{o*} = \delta[(1-\varphi(\theta))\beta^o p - \frac{\breve{w}^o - s\varphi(\theta)]}{\alpha^o\eta[1-\varphi(\theta)]} \tag{29}$$

Let $\breve{q}^{o*} = \breve{q}^{c*}, e^{o*} = e^{c*}$, we get equation (30).

$$\alpha^o = \beta^o, \breve{w}^{o*} = \alpha^o c + (\alpha^o - 1)s\varphi(\theta) \tag{30}$$

Equation (31) and equation (32) can be obtained by substituting Equation (30) into Equation (25) and Equation (26).

$$\breve{\pi}_s^{o*} = (1-\alpha^o)\frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\breve{t})\right)}{2p\eta[1-\varphi(\theta)]^2} \tag{31}$$

$$\breve{\pi}_r^{o*} = \alpha^o\frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\breve{t})\right)}{2p\eta[1-\varphi(\theta)]^2} \tag{32}$$

At this time, it can be verified that $\breve{\pi}_s^{o*} + \breve{\pi}_r^{o*} = (1-\alpha^o)\breve{\pi}^{c*} + \alpha^o\breve{\pi}^{c*} = \breve{\pi}^{c*}$. So, when $\alpha^o = \beta^o$, and $\breve{w}^{o*} = \alpha^o c + (\alpha^o - 1)s\varphi(\theta)$, the combined contract based on revenue sharing and cost sharing can achieve the effect of centralized decision-making.

In addition, in order for all members of the fresh supply chain to accept the combined contract, it is necessary to meet the participation constraint, which means that the profits of all members after applying the combined contract should not be lower than before applying it. It means that $\left\{ \breve{\pi}_s^{o*} \geq \breve{\pi}_s^{d*}\ \breve{\pi}_r^{o*} \geq \breve{\pi}_r^{d*} \right.$. It leads to Equation (33):

$$\begin{cases} \frac{(1-\alpha^o)[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\breve{t})\right)}{2p\eta[1-\varphi(\theta)]^2} \geq \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\breve{t})\right)}{4p\eta[1-\varphi(\theta)]^2} \\ \frac{\alpha^o[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\breve{t})\right)}{2p\eta[1-\varphi(\theta)]^2} \geq \frac{[(1-\varphi(\theta))p - c - s\varphi(\theta)]^2\left(p\delta^2 + \eta b\theta(\breve{t})\right)}{8p\eta[1-\varphi(\theta)]^2} \end{cases} \tag{33}$$

The collation shows that when $(\alpha^o/\beta^o)\epsilon(0.25, 0.5)$, the above inequalities hold simultaneously. Corollary 5 is proved.

7. Example analysis

In order to effectively verify the feasibility of the above model, the parameters are set as follows: $c = 2$ (\$/unit), $p = 8$ (\$/unit), $t = 4$ (day), $\breve{t} = 2$ (day), $\delta = 10$ (\$/unit), $\theta = 0.98$, $s = 0.4$, $\lambda = 0.25$, $\eta = 300$ (\$). x follows the uniform distribution of [0, 200]. The initial parameters used in the numerical analysis are shown above. The value of the cost parameter (e.g. c, p, t) is taken from the study of fresh supply chain management [35], and the value setting of the misrepresentation coefficient λ is taken from the study of Feng and Liu [36]. The numerical setting of the blockchain investment coefficient δ is taken from Jiang and Liu's research on the dual-channel supply chain of blockchain investment [37]. The blockchain cost factor η, transaction time after using blockchain $\breve{t}$, unit deterioration cost s and initial freshness of fresh agricultural products θ are based on the pattern observed in the case study, and the simulation software Matlab is used for numerical simulation to further verify the relevant conclusions. By setting a specific parameter to a particular value, it can be applied to a broader range of common products.

7.1. Impact of the fluctuation of misrepresentation coefficient λ

The misrepresentation coefficient λ can be used to measure the extent to which the rural cooperative conceal the freshness of agricultural products. The fluctuation of λ is of great significance for exploring the influence for cooperative to falsely report the freshness information and strengthening the mutual information trust among the nodes of the supply chain. Here, the floating value of 0.05 is used to analyze the changes of the order quantity and the wholesale price when λ changes within $[0,1]$.

Fig. 3 indicates that the behavior of rural cooperatives concealing freshness information can slightly increase product orders in the short term. Fig. 4 shows the impact of the misrepresentation coefficient on the wholesale price before and after investing in blockchain technology. And the wholesale price will gradually increase with the decrease of λ before investing in blockchain technology. A comprehensive comparative analysis reveals the following conclusions:

① When the freshness of agricultural products is highly distorted, the short-term profitability of rural cooperatives will increase. And the more distorted the freshness information is, the higher the wholesale price supermarkets need to pay.

② There is a threshold value exists. When the misrepresentation coefficient falls below 0.5, the rural cooperative can obtain a short-term price advantage from the supply chain transaction without blockchain technology intervention. At this time, blockchain investment could help the supermarket correct agricultural product information, shorten transaction time, and ultimately obtain a reasonable wholesale price. From the perspective of reducing the procurement cost, when the rural cooperative maliciously exaggerate, the supermarket is more inclined to choose to invest in the blockchain technology.

When the false statement coefficient is higher than 0.5, the wholesale price after applying blockchain technology is higher than before. Although the supermarket cannot obtain the true freshness information of agricultural products, they can still obtain a lower procurement cost. And the rural cooperative can actually obtain a higher wholesale price through the application of the blockchain technology. Therefore, in terms of the subject of malicious misreporting, if a rural cooperative decides to falsify, its falsification coefficient needs to be less than 0.5 in order to increase short-term profit. At this time, the application of the blockchain technology will be beneficial for the supermarket to save procurement costs and transaction fees. This conclusion is exactly consistent with Corollary 3.

Based on the above combination, it can be found that the cooperative can increase the volume of orders from the supermarket in the short term by falsely reporting freshness. However, from the perspective of sustainable development as a whole, in markets with persistent information asymmetry, especially in the fresh supply chain market where freshness information is highly demanded, misreporting behavior poses a challenge to the stability of the entire supply chain. Asymmetric product information leads to the supermarket making incorrect market decision, which also reduces the overall efficiency of the supply chain. As a result, some measures should be taken to enhance the transparency of product information. For example, on one hand, punishment mechanisms can be designed to increase the risks and costs of information hiding. On the other hand, advanced information technologies such as blockchain can be utilized to enhance the transparency and accuracy of information in the fresh supply chain.

7.2. Impact of the fluctuation of the blockchain cost coefficient η

As the industry technology continues to mature, the application cost of blockchain will show a downward trend. Subsequently, this change may trigger the adjustment of the fresh supply chain to the investment decision of blockchain technology. Therefore, in order to analyze the impact of the technology cost changes on supply chain performance and its strategies, we choose 40 as the unit floating value, compare the differences of the fresh supply chain optimization under different decision-making methods in $\eta\in(0,1000]$.

Fig. 5 and Fig. 6 show the changes of the optimal order quantity and the total profit of the fresh supply chain under different decision-making modes when the blockchain cost coefficient η fluctuates, respectively. Fig. 7 shows the changes of the all members'

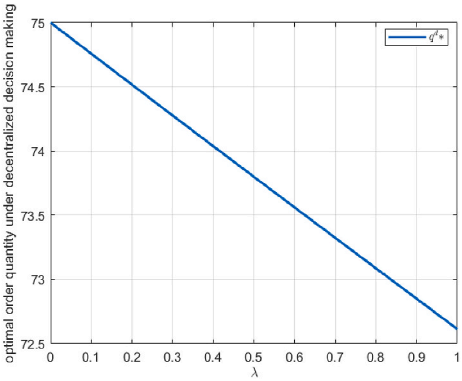

Fig. 3. The influence of λ on the optimal order quantity.

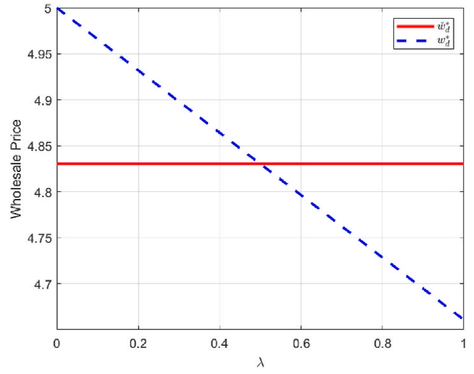

Fig. 4. The effect of λ on the optimal wholesale price.

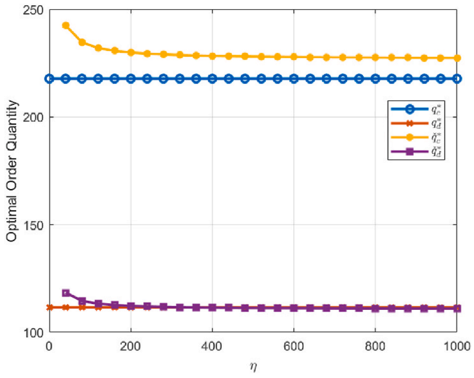

Fig. 5. The effect of η on the optimal order quantity.

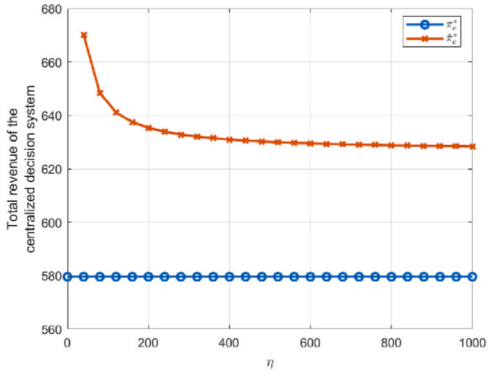

Fig. 6. The effect of η on the total revenue of the centralized decision system.

payoffs under the decentralized decision when the blockchain cost coefficient η fluctuates. Fig. 8 depicts the impact of blockchain cost coefficient fluctuation on the investment cost and the deterioration cost of supermarket under decentralized decision-making.

A comprehensive comparative analysis reveals the following conclusions:

① Compared to decentralized decision-making, the centralized decision-making can better utilize information.

From Fig. 5, it can be found that whether blockchain technology is applied or not, the optimal order quantity of supermarket under the centralized decision-making model significantly exceeds that of the decentralized model. This implies that the centralized decision-making can make better use of information by considering the overall situation, allowing supermarket to respond more swiftly and accurately to market changes.

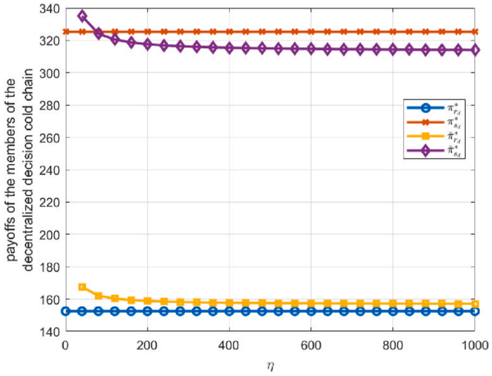

Fig. 7. The effect of η on the payoffs of the members of the decentralized decision fresh supply chain.

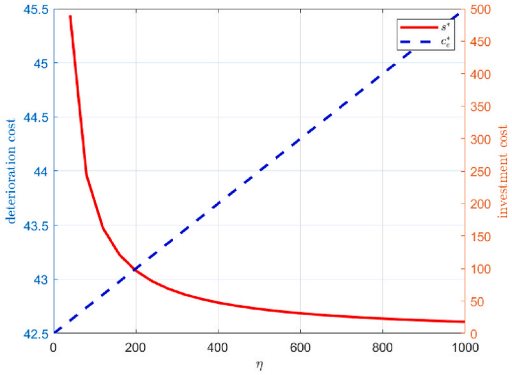

Fig. 8. The effect of η on the investment cost and the deterioration cost in decentralized decision technology.

② The introduction of blockchain technology can effectively enhance the advantages of centralized decision-making in the supply chain.

When blockchain technology is introduced under the centralized decision-making model, the supermarket's order quantity increases compared to when blockchain technology is not used in Fig. 5. Moreover, from Figs. 5 and 6, it can be found that as the decrease in the cost coefficient of blockchain, especially η $\in (0, 200)$, the supermarket's order quantity and the total profit of the supply chain are all significantly increasing.

③ The reduction of the blockchain cost coefficient can slightly improve the performance of supply chain members under decentralized decision-making.

By combining Figs. 5 and 7, it can be observed that the increase in the order quantity and individual member profits only occurs when η falls below a certain threshold. And the profit of the rural cooperative is much higher than that of the supermarket, highlighting the cooperative's dominant role in the supply chain. However, regardless of how the blockchain cost factor changes, the profit of the rural cooperative still accounts for a significant proportion of the supply chain profit.

④ For the rural cooperative under the decentralized decision-making, the application of blockchain technology has a threshold boundary ($\eta = 200$). However, supermarkets can always obtain profits higher than before investing in blockchain technology.

The curve changes in Fig. 7 indicate that for the rural cooperative, blockchain technology does not always lead to an increase in its profit. When $\eta > 200$, the application of blockchain technology will cause profit losses for the rural cooperative. Thus, when the technology cost of blockchain is high, rural cooperatives may not accept the promotion and application of blockchain technology by supermarkets. And the threshold does not exist in the profit fluctuation of the supermarket under decentralized decision-making.

⑤ The increase in the cost coefficient of blockchain will trigger a decelerated reduction in the deterioration cost of fresh supply chain.

From Fig. 8, it can be found that the investment cost and η are positively correlated. But as η increases, the deterioration cost of supply chain is continuously decreasing, and its downward trend is slowing down. In other words, the reduction of blockchain cost coefficient will lead to an increase in the deterioration cost, but in terms of numerical difference, the absolute value of the change in deterioration cost is not significant. It should be noted that the total deterioration cost of supply chain is calculated by $s\varphi(\theta)\check{q}^d$ in equation (17).

At the root cause, on the one hand, the increase in η will lead to a decrease in order quantity (as observed in Fig. 5), resulting in a corresponding decrease in the amount of agricultural product spoilage, and thus a reduction in the total supply chain deterioration cost. On the other hand, the perishable nature of the product itself means that regardless of changes in η, there will always be a certain level of spoilage in the supply chain. The increase of η will cause a decrease in the total deterioration cost, but it will not eliminate the deterioration cost.

In conclusion, the application of blockchain technology is not beneficial to all subjects of the fresh supply chain. Only when the cost factor of blockchain is below a certain threshold, all members will agree to implement this technology. Therefore, when applying blockchain technology, it is necessary to pay more attention to the changes in the cost factor of blockchain. By promptly adjusting the corresponding investment and procurement strategies, the fresh supply chain can achieve higher returns. Meanwhile, some contracts should also be designed to compensate for the profit loss of rural cooperatives due to high technology cost.

7.3. *Impact of combination contract coordination coefficient α^o, β^o*

In order to further explore the influence of the coordination ratio of the combined contract on the investment level of blockchain technology, the order quantity and the profits of supply chain members, let $\eta = 300$, then, 0.1 and 0.05 are selected as unit floating values respectively. The results of the combined contract coordination in $(\alpha^o, \beta^o) \in (0, 1)$ are compared, as shown in Figs. 8 and 9.

By analyzing Figs. 9 and 10 comprehensively, the following conclusions can be drawn.:

① When the ratio of revenue-cost sharing between rural cooperative and supermarket is equal, i.e. $\alpha^o = \beta^o$, the level of investment in blockchain technology and the order quantity of the supermarket achieve the effect of the centralized decision-making under blockchain technology. Then the combined contract can better realize the synergistic effect of the fresh supply chain as a whole.

② The coordination role of the revenue-cost sharing contract in the fresh supply chain becomes ineffective beyond a certain range. When α^o/β^o is greater than 0.5 or α^o/β^o is less than 0.25, the coordinating effect of the combined contract is ineffective. In other words, the effective coordination range of the revenue-cost sharing is $\alpha^o/\beta^o \epsilon (0.25, 0.5)$.

In summary, the combined contract suggested in this paper can effectively coordinate a decentralized decision-making system for implementing blockchain investments, but there is a applicable boundary. When the boundary is exceeded, the combination contract becomes invalid. Participants in the supply chain can decide how to allocate the profit-cost sharing ratio within an effective range based on their position and bargaining power in the supply chain.

8. Conclusions, discussions and future research

8.1. *Conclusions*

With the continuous improvement of consumption level, the fresh supply chain has become an increasingly important focus for management and innovation. However, the advancement of technology and the acceleration of the globalization process have not only optimized resource allocation but also intensified the pressure of multi-source information transmission in the supply chain. Issues such as false reporting and distorted information transmission seriously hinder the further development of the fresh supply chain. In view of this, this article conducts in-depth research on the application of the blockchain technology to solve the problem of information

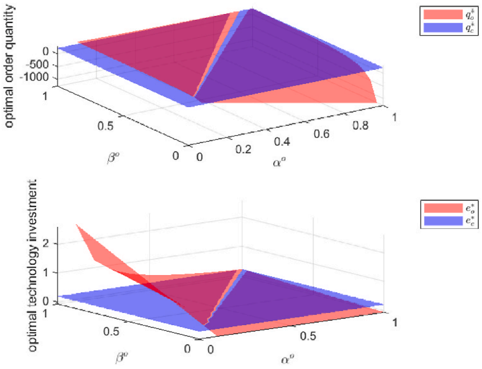

Fig. 9. The effect of (α^o, β^o) on the order quantity and technology investment level.

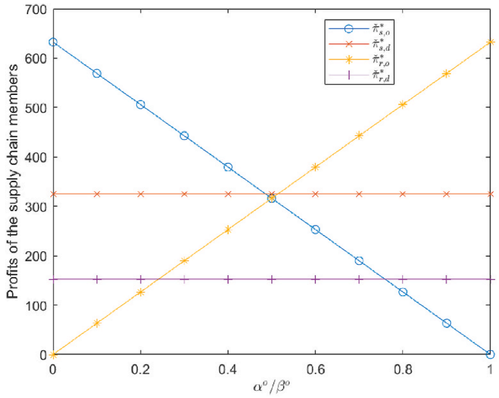

Fig. 10. The effect of (α^o/β^o) on the profits of the supply chain members.

asymmetry in freshness of agricultural products in the supply chain.

The supply chain game models are established separately under different decision-making modes before and after blockchain investment. The models fully consider the dual losses of quality and quantity of fresh agricultural products during the flow process. In addition, when using blockchain technology to solve the problem of freshness information asymmetry, not only the joint impact of freshness and blockchain technology investment on market demand is considered in this paper, but also the impact of blockchain application on transaction time is quantified and incorporated into the analysis of the game models. By comparing the differences in decision-making patterns in different scenarios and the balance solutions and profits of the fresh supply chain before and after blockchain technology investment, we have obtained the investment threshold of blockchain technology in different scenarios. Subsequently, a revenue-cost sharing contract is designed to improve the supply chain performance in decentralized decision-making. Finally, the results of numerical simulation not only validate the feasibility of the models and the combined contract, but also analyze the factors affecting the fresh supply chain performance under different scenarios.

8.2. Discussions

Some important discussions can be drawn and provide references for practical management. First, whether or not investing in blockchain technology, the centralized decision-making mode has significant advantages over the decentralized decision-making mode in terms of the order quantity and the supply chain profit. And the advantages of the centralized decision-making mode can be further enhanced when blockchain technology is introduced. However, regardless of the decision-making mode, there is a investment boundary for the application of blockchain technology. Especially under the centralized decision-making, if and only if the investment cost meets certain conditions, the investment of supermarkets in blockchain can only contribute to the overall performance improvement of the fresh supply chain if the investment cost meets certain conditions.

In fact, blockchain technology not only provides an immutable and fully transparent data sharing platform for all participants in the fresh supply chain, accelerating transaction processes and ensuring transaction security, but also provides a visual product quality supervision channel for end consumers, effectively stimulating consumption. At the same time, it can also compensate for the shortcomings of centralized decision-making in organizational structure and assist in establishing trust throughout the entire chain. Therefore, in terms of overall supply chain performance improvement, enterprises of the fresh supply chain should actively promote the application of blockchain technology in daily transactions.

Second, under the decentralized decision-making mode, when the investment cost meets certain conditions, investing in blockchain is not only beneficial for supermarkets and consumers to grasp authentic information about agricultural products, but also advantageous for the revenue enhancement of supermarkets. However, the introduction of this technology is not always beneficial for all supply chain participants. When there is not serious information distortion in the upstream cooperatives and the cost coefficient of blockchain exceeds a certain threshold, the application of the blockchain technology will lead to a reduction in the order quantity of supermarkets, resulting in a reduction in rural cooperatives income.

It can be found that compared to the centralized decision-making, the application and promotion of blockchain technology under the decentralized decision-making are subject to more constraints and limitations. When product information on the supply chain is severely distorted, rural cooperatives are more likely to gain opportunity benefits from misreporting behavior. And the willingness of supermarkets to invest in blockchain technology is also stronger. However, regardless of whether supermarkets invest in blockchain or not, decentralized decision-making alone cannot achieve optimal performance for the supply chain and its members. At this point, it is necessary and important to establish a reasonable contract.

Third, when the application cost of blockchain at the unit level tends to a lower level, the fluctuations of its value will have a significant impact on the performance of supply chain members and deterioration cost. In fact, as blockchain technology continues to mature and its applicable scenarios continue to expand, the unit application cost is showing a trend of continuous decline. This will not only help save investment costs for supermarkets, but also indirectly stimulate increased consumer demand through blockchain investment level, thereby driving the performance of various members of the fresh supply chain. Of course, it should be noted that in the case of constant quantity loss of agricultural products, an increase in order quantity will lead to a small-scale increase in supply chain deterioration cost.

Therefore, the application of blockchain technology in the fresh food supply chain and its improvement effect on supply chain performance also depend on the effective control of the technology application cost. In management practice, the reduction of technology application costs not only comes from the maturity of the technology itself, but also can be achieved through joint application, technology service leasing and other means to effectively control application costs.

Fourth, while the application of the combined contract can improve supply chain performance under decentralized decision-making, it also has a threshold boundary, and the contract will become invalid when it exceeds the threshold range. When the sharing ratio of revenue sharing and cost contract is equal, the fresh supply chain can realize Pareto improvement and achieve a win-win effect.

8.3. Future research

Although this article focuses on the introduction of the blockchain technology in the supply chain of fresh agricultural products to address the issue of false freshness information, it only applies to the single model of "the rural cooperative and the supermarket" and does not involve the optimization of fresh supply chain decision-making with multiple nodes involved. When blockchain technology is applied in more complex supply chains, its impact on the transaction process and information sharing process will become more complex, which will be an important direction for future research in this field. In addition, this study only designed a profit-cost sharing contract to coordinate the fresh supply chain. In the future, more types of combined contracts can be introduced to explore their impact on the promotion and application of blockchain technology, and compare their respective applicable scenarios and co-ordination effects.

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Data availability statement

The data included in article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Xin Yang: Writing – review & editing, Conceptualization. **Mingjing Liu:** Writing – original draft, Supervision. **Jinyu Wei:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Yaoxi Liu:** Writing – review & editing.

Declaration of competing interest

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References

[1] Our country fruit and vegetable loss of 400 billion a year, what is the method of crack [EB/OL]. [2022-06-26]. https://new.qq.com/omn/20211130/20211130A03F9700.html.

[2] C.Q. Tan, Y.Q. Zeng, W.H. Ip, C.H. Wu, B2C or O2O? The strategic implications for the fresh produce supply chain based on blockchain technology, Comput. Ind. Eng. 183 (2023) 109499, https://doi.org/10.1016/j.cie.2023.109499.

[3] Q.X. Li, H.M. Ji, Y.M. Huang, The information leakage strategies of the supply chain under the block chain technology introduction, Omega 110 (2022) 102616, https://doi.org/10.1016/j.omega.2022.102616.

[4] Z.J. Xie, H. Kong, B. Wang, Dual-chain blockchain in agricultural E-commerce information traceability considering the viniar algorithm, Sci. Program. (2022) 1–10, https://doi.org/10.1155/2022/2604216, 2022.

[5] I.A. Omar, R. Jayaraman, M.S. Debe, H.R. Hasan, K. Salah, M. Omar, Supply chain inventory sharing using ethereum blockchain and smart contracts, IEEE Access 10 (2022) 2345–2356, https://doi.org/10.1109/ACCESS.2021.3139829.

[6] Y.P. Liu, B. Yan, X.X. Chen, Coordination of dual-channel supply chains with uncertain demand information, IMA J. Manag. Math. 34 (2023) 333–353, https://doi.org/10.1093/imaman/dpac011.

[7] M. Li, L. He, G.C. Yang, Z. Lian, Profit-sharing contracts for fresh agricultural products supply chain considering spatio-temporal costs, Sustainability 14 (2022) 2315, https://doi.org/10.3390/su14042315.

[8] L. Liu, F.T. Li, Differential game modelling of joint carbon reduction strategy and contract coordination based on low-carbon reference of consumers, J. Clean. Prod. 277 (2020) 123798, https://doi.org/10.1016/j.jclepro.2020.123798.

[9] Z. Zhao, Y. Cheng, Two-stage decision model of fresh agricultural products supply chain based on option contract, IEEE Access 10 (2022) 119777–119795, https://doi.org/10.1109/ACCESS.2022.3221974.

[10] B. Dan, S. Ding, H.Y. Fu, Fresh supply chain coordination by wholesale market in sale place under information asymmetry, J. Manag. Sci. China 16 (2013) 40–50.

[11] Z.Y. Tang, X.X. Luo, X.H. Chen, Research on supply chain coordination of fresh agricultural products based on options under tw o kinds of information asymmetry, Forecast 38 (2019) 76–83.

[12] B. Yan, T. Wang, Y.P. Liu, Y. Liu, Decision analysis of retailer-dominated dual-channel supply chain considering cost misreporting, Int. J. Prod. Econ. 178 (2016) 34–41, https://doi.org/10.1016/j.ijpe.2016.04.020.

[13] H.H. Feng, X. Wang, Y.Q. Duan, J. Zhang, X.H. Zhang, Applying blockchain technology to improve agri-food traceability: a review of development methods, benefits and challenges, J. Clean. Prod. 260 (2020) 121031, https://doi.org/10.1016/j.jclepro.2020.121031.

[14] K. Gopi, D. Mazumder, J. Sammut, N. Saintilan, Determining the provenance and authenticity of seafood: a review of current methodologies, Trends Food Sci. Technol. 91 (2019) 294–304, https://doi.org/10.1016/j.tifs.2019.07.010.

[15] Y.J. Wang, Research on supply chain financial risk assessment based on blockchain and fuzzy neural networks, Wireless Commun. Mobile Comput. 2021 (2021) 1–8, https://doi.org/10.1155/2021/5565980.

[16] A. Arena, A. Bianchini, P. Perazzo, C. Vallati, G. Dini, BRUSCHETTA: an IoT blockchain-based framework for certifying extra virgin olive oil supply chain, International Conference on Smart Computing in (2019) 173–179, https://doi.org/10.1109/SMARTCOMP.2019.00049.

[17] F. Longo, L. Nicoletti, A. Padovano, Estimating the impact of blockchain adoption in the food processing industry and supply chain, Int. J. Food Eng. 16 (2020) 20190109, https://doi.org/10.1515/ijfe-2019-0109.

[18] P. Liu, Investment decisions of blockchain-based anti-counterfeiting traceability services in a high-quality fresh supply chain of China, Agric. For. 12 (2022) 829, https://doi.org/10.3390/agriculture12060829.

[19] P. Liu, X.Y. Cui, Z.R. Zhang, W.W. Zhou, Y. Long, Pricing strategies of low-carbon enterprises in the Yellow River Basin considering demand information and traceability services, Kybernetes 52 (2023) 304–327, https://doi.org/10.1108/K-06-2021-0529.

[20] H. Qi, Z. Li, X. Zhang, Blockchain adoption decision analysis of fresh supply chain considering 3PL's misreporting behavior, Procedia Comput. Sci. (2023) 642–649, https://doi.org/10.1016/j.procs.2023.08.033.

[21] S.K. Dey, B.C. Giri, Coordination of a sustainable reverse supply chain with revenue sharing contract, J. Ind. Manag. Optim. 18 (1) (2022) 487–510, https://doi.org/10.3934/jimo.2020165.

[22] M. Wang, L.D. Zhao, M. Herty, Joint replenishment and carbon trading in fresh food supply chains, Eur. J. Oper. Res. 277 (2019) 561–573, https://doi.org/10.1016/j.ejor.2019.03.004.

[23] Q. Zheng, L. Zhou, T.J. Fan, P. Ieromonachou, Joint procurement and pricing of fresh produce for multiple retailers with a quantity discount contract, Transp. Res., Part E Logist. Transp. Rev. 130 (2019) 16–36, https://doi.org/10.1016/j.tre.2019.08.013.

[24] C.Q. Wu, K.P. Li, T.Q. Shi, Supply chain coordination with two-part tariffs under information asymmetry, Int. J. Prod. Res. 55 (2017) 2575–2589, https://doi.org/10.1080/00207543.2016.1240383.

[25] C.F. Zhou, W.S. Tang, Y.F. Lan, Supply chain contract design of procurement and risk-sharing under random yield and asymmetric productivity information, Comput. Ind. Eng. 126 (2018) 691–704, https://doi.org/10.1016/j.cie.2018.10.022.

[26] Z. Mobini, W. Van Den Heuvel, A. Wagelmans, Designing multi-period supply contracts in a two-echelon supply chain with asymmetric information, Eur. J. Oper. Res. 277 (2019) 542–560, https://doi.org/10.1016/j.ejor.2019.03.002.

[27] A. Ranjbar, J. Heydari, M. Madani Hosseini, D. Yahyavi, Green channel coordination under asymmetric information, Ann. Oper. Res. 329 (2023) 1049–1082, https://doi.org/10.1007/s10479-021-04284-w.

[28] V. Pavlov, E. Katok, W. Zhang, Optimal contract under asymmetric information about fairness, Manuf. Serv. Oper. Manag. 24 (2022) 305–314, https://doi.org/10.1287/msom.2020.0945.

[29] L. Wang, B. Dan, Research on preservation strategies for fresh produce considering quality and quantity loss control, Chin. J. Manag. Sci. 31 (8) (2023) 100–110, https://doi.org/10.16381/j.cnki.issn1003-207x.2020.1715.

[30] S.Y. Wang, Y.M. Jiang, J.J. Mou, Inventory and pricing decision of an integrated cold chain based on freshness, Chin. J. Manag. Sci. 26 (7) (2018) 132–141, https://doi.org/10.16381/j.cnki.issn1003-207x.2018.07.014.

[31] P.Y. Chen, X. Liu, P. Zhou, S.X. Zhu, The interplay between strategic inventories and cost misreporting in supply chains, Transp. Res., Part E Logist. Transp. Rev. 163 (2022) 102737, https://doi.org/10.1016/j.tre.2022.102737.

[32] Y.L. Yu, T.J. Xiao, Analysis of cold-chain service outsourcing modes in a fresh agri-product supply chain, Transp. Res., Part E Logist. Transp. Rev. 148 (2021) 102264, https://doi.org/10.1016/j.tre.2021.102264.

[33] Z.L. Yi, Y.L. Wang, Y. Liu, Y.J. Chen, The impact of consumer fairness seeking on distribution channel selection: direct selling vs. Agent selling, Prod. Oper. Manag. 27 (2018) 1148–1167, https://doi.org/10.1111/poms.12861.

[34] S. Hayrutdinov, M.S.R. Saeed, A. Rajapov, Coordination of supply chain under blockchain system-based product lifecycle information sharing effort, J. Adv. Transport. (2020) 1–10, https://doi.org/10.1155/2020/5635404, 2020.

[35] L. Liu, F.T. Li, Investment decision and coordination of blockchain technology in fresh supply chain considering retailers' risk aversion, J. Ind. Eng. Eng. Manag. 36 (1) (2022) 13, https://doi.org/10.13587/j.cnki.jieem.2022.01.014.

[36] Y. Feng, Z. Liu, Analysis of cost misreporting in A fresh agri-products supply chain with TPL's participation, Soft Sci. 9 (2017) 133–137, https://doi.org/10.13956/j.ss.1001-8409.2017.09.29.

[37] Y.C. Jiang, C. Liu, Research on carbon emission reduction and blockchain investment under different dual-channel supply chains, Environ. Sci. Pollut. Res. 29 (2022) 65304–65321, https://doi.org/10.1007/s11356-022-20366-z.