Effects of Blockchain Traceability Input on Fresh Supply Chain Pricing Rules with the Freshness Information Unreliability

Mengjuan Li, Pan Liu, Wenwen Pan, and Changxia Sun

***Abstract*—Considering the impact of freshness information unreliability on fresh supply chain revenues, this paper discusses the optimal pricing problem after fresh supply chain members purchase and apply blockchain traceability service (BCTS). A fresh products producer and a retailer were selected as this study object. Next, considering that the untrustworthy level of freshness information is critical for decision makers to adopt BCTS, the market demand function was modified. Based on the master-slave game, the revenue models of the fresh producer and retailer were established under the proposed four investment conditions, and the supply chain was coordinated when a price discount and revenue-sharing (PDRS) contract was applied. The conclusions of this research are as follows: (1) In some revenue-sharing interval, adopting this contract can stimulate the stakeholders' enthusiasm and improve supply chain efficiency; (2) As the investment of producer and retailer in BCTS increases, the unreliability coefficient of freshness information (UCFI) will decrease. Furthermore, the retailer's input is more sensitive to UCFI than producer; (3) The optimal retail price is positively related to the retailer's input in BCTS, while the optimal wholesale price is inversely related. They are positively correlated with the producer's unit BCTS cost, but not with the UCFI.**

***Index Terms*—blockchain; fresh supply chain; traceability service; pricing; the unreliability coefficient of freshness information; game theory**

I. Introduction

With the significant improvement of residents' living standards and the special background of COVID-19, consumers have begun to pay more attention to food safety and have a stronger demand for product traceability information [1]-[2]. Therefore, countries have begun to establish and implement food traceability systems [3]. More and more scholars began to focus on the establishment of food traceability system [4]. However, the data of the traditional traceability system is mostly centralized storage, and its highly centralized mode has some problems such as opaque transaction and easy tampering in the sharing process [5]-[6]. Once something goes wrong, it's hard to find the source [7]. As an integrated, distributed, and tamper-proof database technology, blockchain technology can prevent the data from being tampered with the blocks in the participant chain without establishing a trust relationship, enhance the trust of stakeholders, and promote product authenticity and reliability information [8]. At the same time, every transaction on the blockchain can be traced back, which greatly reduces member fraud. For the fresh products, freshness not only reflects their quality but also affects consumers' purchase decisions [9]. So, to sell more products, the fraudulent behavior regarding freshness information is common. To prevent this kind of fraud, some fresh supply chain members began to purchase and apply it [10]. However, after the application of blockchain traceability service, what is the pricing laws of products? How to set the prices can increase investors revenues? These are some important issues for enterprises after using BCTS.

Studies have shown that using BCTS can improve consumers' trust level on freshness information in the fresh supply chain [11]. However, the freshness information unreliability may influence the decision of stakeholders to adopt the BCTS. Thereupon, in this paper, we'll talk about the stakeholders' pricing rules considering the freshness information unreliability and BCTS input. To this end, firstly, according to the new demand function, the revenue functions under the four investment modes are established. Secondly, the investment conditions are obtained by comparing the returns of chain members in different investment modes. Thirdly, by analyzing the impacts of the product freshness and its unreliability coefficient on revenues, the pricing rules are obtained. Finally, numerical simulation is used to verify the conclusions of this paper. The pricing problems are studied by contrasting the total revenues under the proposed four conditions. By analyzing the revenue functions of supply chain members before and after applying BCTS, the optimal pricing and optimal revenues under different investment modes are obtained, and the pricing laws are

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analyzed. Considering the decision-making basis and game relationship among supply chain members, the master-slave game model is selected.

The innovations of this paper are as follows: (1) In the context of blockchain, the corresponding demand function is revised by considering the freshness information unreliability of fresh products. (2) A PDRS contract is advised to encourage the fresh stakeholders to use BCTS to achieve coordination. (3) For the BCTS, its input cost, revenue sharing coefficient and the unreliability in the freshness of fresh products on pricing are analyzed.

II. Materials and Methods

A. The Use of Traceability Service in the Fresh Supply Chain

For the fresh food industry, the use of traceability service mainly focuses on the development of fresh e-commerce, the quality and safety of fresh products, the purchasing tendency of fresh products consumers, and the investment decision of the fresh supply chain.

(1) For fresh e-commerce field, scholars mostly study the influence of traceability investment on the development of fresh e-commerce. Liao et al. [12] conducted research on traceable fresh food consumer behavior and put forward some suggestions to promote the development of fresh e-commerce. Shao et al. [13] analyzed Stackelberg game between consumers and suppliers in the traditional B2C mode, and the results showed that the purchase demand would increase with the increase of consumers' trust in producers, indicating that product quality traceability has become the core competitiveness of fresh e-commerce.

(2) In the field of fresh products quality and safety, Tagarakis et al. [14] proposed a user-friendly open access traceability system to implement this platform to monitor the entire supply chain. Rahman et al. [15] reviewed research on the safety of traceability system in fisheries supply chain management. Zhou et al. [16] designed and implemented a fresh pork quality and safety information traceability system.

(3) In the field of fresh products purchase intention, high-quality traceability service can display the quality information of fresh products in multiple dimensions and improve consumers' purchase intention [17]. Cui [18] found that consumers have a strong willingness to buy fresh products with traceable management characteristics through research on the changes in the fresh food consumption market. A study on pork consumption preferences and willingness to pay in Taiwan's traditional markets found that 80% of consumers in traditional markets tend to pay high prices for traceable [19].

(4) In the area of fresh supply chain investment decision making, Yang et al. [20] constructed profit models of centralized and decentralized supply chains before and after the application of RFID technology based on Stackelberg game, and studied the investment cost threshold. Zhu et al. [21] combined the optimal control theory and differential game theory to analyze the optimal retrospective service investment.

Through the above analysis, we can find that most of the previous researches focused on the development and utilization of traceability system, and rarely mentioned the trust on products traceability. Subsequently, the authenticity and reliability of the traceability information of fresh products are guaranteed as blockchain technology begins to emerge and apply. Details will be described in the following section.

B. The Use of Blockchain Technology in the Fresh Supply Chain

In 2008, the concept of blockchain was first proposed [22]. In the years that followed, blockchain became a core component of bitcoin, the electronic currency. Its characteristics of high transparency, decentralization, trustlessness, collective maintenance, anonymity and so on are well applied to verify the authenticity of information [23].

In recent years, there are many academic studies about the application of blockchain in the fresh supply chain [24]-[27]. However, few studies have been conducted on fresh food supply chain operation decisions, especially pricing strategies, based on game theory. For example, based on the Stackelberg game, Chen et al. [28] studied the impact of blockchain usage on false reporting of fresh information by producers, and discussed changes in supply chain benefits with or without application. Wu et al. [29] analyzed the optimal decisions of fresh supply chain based on blockchain traceability system under three main agency situations respectively, and found that investing blockchain is not always profitable. Liu et al. [30] used blockchain technology to suppress the phenomenon of false reporting of fresh food by suppliers, and studied the changes in the equilibrium solution of the fresh food supply chain under different circumstances before and after the introduction of blockchain technology. Based on the impact of loyalty on products security demand, Sun et al. [31] considered the optimal pricing of the supply chain for the decentralized and centralized decision-making model driven by both the traditional mode and blockchain technology, and used game theory to solve the equilibrium solution of the model. Xu et al. [32] used Stackelberg game to realize supply chain coordination after using green technology in the context of blockchain. Lin et al. [33] built a game model according to the characteristics of the blockchain to analyze the incomplete trust of consumers in green agricultural products and the high transaction cost of the supply chain, and analyzed the decision-making conditions before and after the implementation of the green supply chain. Hayrutdinov et al. [34] compared the Nash equilibrium solutions of different scenarios under product life cycle information sharing efforts using game theory reverse induction in a blockchain system.

To sum up, we find that most of the previous researches are the fusion application analysis and technical analysis of supply chain management and blockchain, and rarely involve the impact of BCTS input on stakeholder pricing. There are some research deficiencies: (1) Most studies concentrate on the use of blockchain in fresh supply chains, but few on stakeholder pricing issues after the adoption of BCTS. (2) From the game theory, few studies concern on the effects of the unreliability of freshness information on the market demand and supply chain benefits. Therefore, this paper focuses on the fresh supply chain pricing problems after using BCTS. At the same time, during the modeling process, we propose incentive policies to achieve synergy in the fresh food supply chain and allow stakeholders to obtain higher benefits.

III. PARAMETERS DESCRIPTION

A. Parameters description

TABLE 1
PARAMETERS DESCRIPTION

Parameters	Significance
i	The four investment models, here, $i=\{Q,H,J,C\}$ .Their specific explanations will be given below.
a	Potential market demand.
e	Price sensitivity of demand.
$\varphi(t)$	The fresh products loss function.
$\theta(t)$	The fresh products freshness decay function.
t^i	The fresh products circulation time in case i , here, $t\in[0,T]$.
T	The fresh products' life cycle.
c_p	The fresh products' unit production cost.
c_s	The unit circulation cost.
c_{ow}	Producer's BCTS cost.
c_{or}	Retailer's BCTS costs.
π_r^i	Retailer's revenues in case i .
π_w^i	Producer's revenues in case i .
γ^i	The UCFI, here, $\gamma^i\in[0,1]$.
D^i	Market demand in case i , here, it equals the quantity of goods ordered by the retailer.
p^i	The retail price in case i .
w^i	The wholesale price in case i .
ρ	The revenue-sharing ratio of retailer.

B. Research Question

1) *Structure of the Fresh Supply Chain*

In this research, a fresh products producer and a retailer were selected as the research object. After investment in blockchain traceability service, the corresponding fresh supply chain system is shown in Fig. 1.

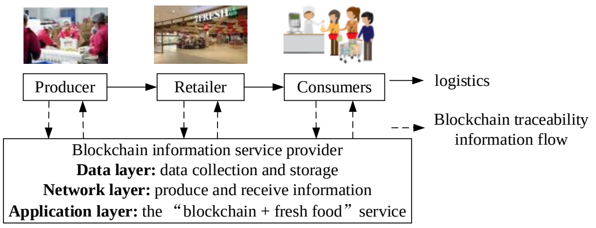

Fig. 1. Fresh supply chain structure after adopting the BCTS

2) *Decision Process*

Generally speaking, the producers and retailers make investment decisions based on the maximization of their own interest, that is, the competition between them conforms into the master-slave game. Before adopting BCTS, case *Q*, the producer as the game leader provides fresh products with a life cycle of T and sets the wholesale price w^Q considering the circulation losses and investment costs. As the retailer sets the order quantity based on the wholesale price w^Q . The producer determines the shipments of fresh products based on the order volume and loss of circulation. Once the retailer receives the products, the retail price p^Q will be determined based on market reaction and freshness.

After using BCTS, case *H*, firstly, the producer provides fresh products with a life cycle T and determines the unit BCTS cost c_{ow} considering the market circulation loss and market demand. According to the new cost, the wholesale price w^H is set. Then, as the post-decision retailer, sets the quantity of orders D^H based on the wholesale price w^H . The producer determines the shipments of fresh products based on the order volume and circulation losses. Upon receipt of the fresh products, retail prices p^H will be determined by the retailer based on market response, product freshness and unit BCTS cost c_{or} .

After using the BCTS, case *J*, stakeholders jointly determine the relevant decision variables. At first, they set the retail price p^J based on the likely market demand D^J , and then determine the shipments of fresh products based on the market demand and new circulation losses. Additionally, they will determine their own unit BCTS costs based on the likely growth in market demand.

After using the BCTS, case *C*, firstly, the producer provides fresh products with a life cycle T . And to incentivize the retailer to place orders and use BCTS, the producer will set a lower wholesale price. In return, the producer receives a share of the revenues from the retailer. Now, the producer as the game leader decides the input cost c_{ow} per unit of BCTS based on the loss rate of new products. The retailer, as the follower of the game, decides the order quantity and the proportion ρ of return profit based on the wholesale price. The producer determines the shipments of fresh products based on the orders and losses from retailers. After receiving the fresh products, the retailer decides the retail price based on the market response, the product freshness, and the unit BCTS input cost c_{or} .

3) *The Modified Demand Function*

The freshness of fresh products has an important influence on the market demand due to its uniqueness, as does the authenticity of products information. According to the *2020 Jingdong blockchain technology practice White paper*, we know that the BCTS can decrease the UCFI and thus increase sales volume, and improve the circulation rate of products. In addition, market demand is very sensitive to price. Considering the loss of fresh products in circulation by Cai et al. [35], we modified the demand function after the input of the BCTS.

$$D^i=(1-\gamma^i)(a-ep^i)\theta(t^i) \quad (1)$$

After using BCTS, the fresh products circulate more efficiently. Therefore, before and after the BCTS investment, the corresponding circulation time $t^Q>t^H$. Assuming that the circulation time of fresh products is the same after using the BCTS, that is $t^H=t^J=t^C$. Then, $\theta(t^H)=\theta(t^J)=\theta(t^C)>\theta(t^Q)$. In general, $0\le c_p+c_s\le w^i\le p^i$.

C. Research Hypothesis

1) Due to the perishable nature of fresh products, the market demand is assumed to be equal to the quantity ordered by the retailer. The producer has the sufficient production capacity.

2) Following the consumers psychology of good quality and low price, it is assumed that they are more inclined to spend less money on products with higher freshness.

3) Since the BCTS can shorten the transaction time, the circulation time will be shortened after application. To guarantee that the retailer receives a valid quantity of products, the producer ships $D^i/\varphi(t^i)$.

4) For the full supply chain traceability, it is assumed that both the retailer and producer invest in the, $*$ indicates the optimal decisions.

IV. Four Investment Pricing Models

A. Decision Model in Case of Q

Consumers cannot verify the authenticity of fresh products when the fresh products producer and retailer fail to adopt the BCTS. That would have a negative impact on the UCFI and the products circulation time would be longer than otherwise. At the same time, the producer may lie about the freshness of products. At this point, the revenue functions of the stakeholders can be shown as formula (2) and (3).

$$\pi_w^Q=[w^Q-(c_p+c_s)](1-\gamma^Q)(a-ep^Q)\theta/\varphi(t^Q) \tag{2}$$

$$\pi_r^Q=(p^Q-w^Q)(1-\gamma^Q)(a-ep^Q)\theta(t^Q) \tag{3}$$

Generally, the fresh products producer has a dominant position in the market, so the fresh supply chain conforms to the master-slave game. The optimal solution under this model is solved by the backward induction. Let $\partial\pi_r^Q/\partial p^Q=0$, we can get p^Q. Then plug it into the producer's revenue function. Let $\partial\pi_w^Q/\partial w^Q=0$, the optimal retail price can be obtained. So, the optimal wholesale price and the optimal decisions of fresh supply chain can be got.

$$p^{Q*}=\frac{e(c_p+c_s)+3a\varphi(t^Q)}{4e\varphi(t^Q)} \tag{4}$$

$$w^{Q*}=\frac{e(c_p+c_s)+a\varphi(t^Q)}{2e\varphi(t^Q)} \tag{5}$$

$$D^{Q*}=\frac{\theta(t^Q)(1-\gamma^Q)[a\varphi(t^Q)-ec_p-ec_s]}{4\varphi(t^Q)} \tag{6}$$

$$\pi_w^{Q*}=\frac{\theta(t^Q)(1-\gamma^Q)[a\varphi(t^Q)-ec_p-ec_s]^2}{8e\varphi(t^Q)^2} \tag{7}$$

$$\pi_r^{Q*}=\frac{\theta(t^Q)(1-\gamma^Q)[a\varphi(t^Q)-ec_p-ec_s]^2}{16e\varphi(t^Q)^2} \tag{8}$$

From the non-negative constraint of demand satisfaction, $a\theta(t^Q)>ec_p+ec_s$. And when $a\theta(t^Q)>ec_p+ec_s$, $p^{Q*}\ge w^{Q*}\ge 0$.

Proposition 1:

$$\frac{\partial\pi_w^{Q*}}{\partial\gamma}=-\frac{\theta(t^Q)[a\varphi(t^Q)-ec_p-ec_s]^2}{8e\varphi(t^Q)^2}<0,$$

$$\frac{\partial\pi_r^{Q*}}{\partial\gamma}=-\frac{\theta(t^Q)[a\varphi(t^Q)-ec_p-ec_s]^2}{16e\varphi(t^Q)^2}<0,$$

$$\frac{\partial D^{Q*}}{\partial\gamma}=-\frac{\theta(t^Q)[a\varphi(t^Q)-e(c_p+c_s)]}{4\varphi(t^Q)}<0,\quad \frac{\partial p^{Q*}}{\partial\gamma}=0,\quad \frac{\partial w^{Q*}}{\partial\gamma}=0.$$

According to proposition 1, with the increase of the UCFI, the revenues and market demand of the fresh products producer and retailer will decrease in case *Q*. This may be because the improvement of the UCFI decreases the market demand, which decreases the income of the supply chain members. This is the constant UCFI under the normal market transactions. So, the two optimal prices don't change with it.

B. Decision Model in Case of H

When the stakeholders adopt the BCTS, supply chain information is basically symmetric, and product freshness can be better understood by consumers. By this time, the products can simplify the operation process and shorten the circulation time through automatic identification and data collection. Moreover, it's hard for the producer to lie about the freshness of their products. So, the retailer doesn't wear out by ordering too many products, hence $\varphi(t^Q)<\varphi(t^H)$. Customers can verify the authenticity of quality products, reduce the time to choose products and decrease the UCFI. Now, the revenue functions of the fresh products producer and retailer can be shown as formula (9) and (10).

$$\pi_w^H=[w^H-(c_p+c_s+c_{ow})](1-\gamma^H)(a-ep^H)\theta(t^H)/\varphi(t^H) \tag{9}$$

$$\pi_r^H=(p^H-w^H-c_{or})(1-\gamma^H)(a-ep^H)\theta(t^H) \tag{10}$$

Similarly, the optimal decision under this model can be obtained by backward induction.

$$p^{H*}=\frac{e(c_p+c_s+c_{ow})+\varphi(t^H)(3a+ec_{or})}{4e\varphi(t^H)} \tag{11}$$

$$w^{H*}=\frac{e(c_p+c_s+c_{ow})+\varphi(t^H)(a-ec_{or})}{2e\varphi(t^H)} \tag{12}$$

$$D^{H*}=\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{4\varphi(t^H)} \tag{13}$$

$$\pi_w^{H*}=\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{8e\varphi(t^H)^2} \tag{14}$$

$$\pi_r^{H*}=\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{16e\varphi(t^H)^2} \tag{15}$$

From the non-negative constraint of demand satisfaction, we know $\varphi(t^H)(a-ec_{or})>e(c_p+c_s+c_{ow})$. Now, the total optimal revenues are $\pi^{H*}=\pi_w^{H*}+\pi_r^{H*}=\frac{3\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{16e\varphi(t^H)^2}$.

Proposition 2:

(1) $\frac{\partial p^{H*}}{\partial c_{ow}}=\frac{1}{4\varphi(t^H)}>0$, $\frac{\partial w^{H*}}{\partial c_{ow}}=\frac{1}{2\varphi(t^H)}>0$,

$$\frac{\partial D^{H*}}{\partial c_{ow}}=-\frac{e\theta(t^H)(1-\gamma^H)}{4\varphi(t^H)}<0,$$

$$\frac{\partial\pi_w^{H*}}{\partial c_{ow}}=-\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{4\varphi(t^H)^2}<0,$$

$$\frac{\partial\pi_r^{H*}}{\partial c_{ow}}=-\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{8\varphi(t^H)^2}<0.$$

(2) $\frac{\partial w^{H*}}{\partial c_{or}}=-\frac{1}{2}<0$, $\frac{\partial p^{H*}}{\partial c_{or}}=\frac{1}{4}>0$, $\frac{\partial D^{H*}}{\partial c_{or}}=-\frac{e\theta(t^H)(1-\gamma^H)}{4}<0$,

$$\frac{\partial\pi_w^{H*}}{\partial c_{or}}=-\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{4\varphi(t^H)}<0,$$

$$\frac{\partial \pi_r^{H*}}{\partial c_{or}} = -\frac{\theta(t^H)(1-\gamma^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{8\varphi(t^H)} < 0 .$$

(3) $\frac{\partial p^{H*}}{\partial \gamma} = 0$, $\frac{\partial w^{H*}}{\partial \gamma} = 0$,

$$\frac{\partial \pi_w^{H*}}{\partial \gamma} = -\frac{\theta(t^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{8e\varphi(t^H)^2} < 0 ,$$

$$\frac{\partial \pi_r^{H*}}{\partial \gamma} = -\frac{\theta(t^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{16e\varphi(t^H)^2} < 0 ,$$

$$\frac{\partial D^{H*}}{\partial \gamma} = -\frac{\theta(t^H)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{4\varphi(t^H)} < 0 .$$

According to (1) of proposition 2, in the case of *H*, the two optimal prices will increase with the input of producer's BCTS. And the corresponding revenues and demand decrease. It would be that the producer increases its wholesale price to cover the cost of the BCTS, forcing the retailer to set a higher retail price. An increase in retail price reduces demand, which decreases the profits of the producer and the retailer.

According to (2) of proposition 2, in the case of *H*, the retailer's input into the BCTS is positively related to the retail price and inversely related to the wholesale price and revenues. This is probably because the retailer raises their retail price to cover the cost of the BCTS. The producer cuts wholesale prices to incentivize the retailer to order more fresh products. Higher retail price reduces the demand, resulting in lower profits for the producer and the retailer.

According to (3) of proposition 2, in the case of *H*, with the increase of the UCFI, the demand decreases. So, the revenues of producer and retailer decrease. There is no direct correlation between the two optimal prices and the UCFI. Therefore, investing the BCTS can decrease the UCFI and increase the revenues for the fresh supply chain.

C. Decision Model in Case of J

The fresh supply chain uses the BCTS and jointly determine the retail price in the mode of centralized decision-making. At this point, the total revenues of the whole fresh supply chain can be shown as formula (16).

$$\pi^J = \frac{[\varphi(t^J)(p^J-c_{or})-(c_p+c_s+c_{ow})](1-\gamma^J)(a-ep^J)\theta(t^J)}{\varphi(t^J)} \quad (16)$$

According to formula (16), the optimal retail price p^{J*} can be got. Then, the optimal decisions under this model can be obtained.

$$p^{J*} = \frac{\varphi(t^J)(a+ec_{or})+e(c_p+c_s+c_{ow})}{2e\varphi(t^J)} \quad (17)$$

$$D^{J*} = \frac{\theta(t^J)(1-\gamma^J)[\varphi(t^J)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{2\varphi(t^J)} \quad (18)$$

$$\pi^{J*} = \frac{\theta(t^J)(1-\gamma^J)[\varphi(t^J)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{4e\varphi(t^J)^2} \quad (19)$$

From the non-negative constraint of demand satisfaction, we know $\varphi(t^J)(a-ec_{or}) > e(c_p+c_s+c_{ow})$.

By analyzing the total revenues in model *H* and *J*, we get $\pi^{H*}-\pi^{J*} = \frac{3\theta(t^H)(1-\gamma^J)[\varphi(t^H)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{-16e\varphi(t^H)^2} < 0$, we know $\pi^{H*} < \pi^{J*}$. That is, the total revenues in case *H* is lower than in case *J*. Therefore, the supply chain coordination isn't realized after using the BCTS. Cost sharing contracts always help supply chains coordination [36]. So, a PDRS contract will be designed to realize coordination.

Proposition 3:

(1) $\frac{\partial p^{J*}}{\partial c_{ow}} = \frac{1}{2\varphi(t^J)} > 0$, $\frac{\partial D^{J*}}{\partial c_{ow}} = -\frac{e\theta(t^J)(1-\gamma^J)}{2\varphi(t^J)} < 0$,

$$\frac{\partial \pi^{J*}}{\partial c_{ow}} = -\frac{\theta(t^J)(1-\gamma^J)[\varphi(t^J)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{2\varphi(t^J)^2} < 0 .$$

(2) $\frac{\partial p^{J*}}{\partial c_{or}} = \frac{1}{2} > 0$, $\frac{\partial D^{J*}}{\partial c_{or}} = -\frac{e\theta(t^J)(1-\gamma^J)}{2} < 0$,

$$\frac{\partial \pi^{J*}}{\partial c_{or}} = -\frac{\theta(t^J)(1-\gamma^J)[\varphi(t^J)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{2\varphi(t^J)} < 0 .$$

(3) $\frac{\partial p^{J*}}{\partial \gamma} = 0$, $\frac{\partial D^{J*}}{\partial \gamma} = -\frac{\theta(t^J)[\varphi(t^J)(a-ec_{or})-e(c_p+c_s+c_{ow})]}{2\varphi(t^J)} < 0$,

$$\frac{\partial \pi^{J*}}{\partial \gamma} = -\frac{\theta(t^J)[\varphi(t^J)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{4e\varphi(t^J)^2} < 0 .$$

According to (1) of proposition 3, in the case of *J*, the optimal retail price increases with the increase of the producer's BCTS. This may be because the producer increases the wholesale price to compensate for the cost of the BCTS, forcing the retailer to raise the retail price. Higher retail prices reduce the demand, resulting in lower revenues for the producer and retailer.

According to (2) of proposition 3, in the case of *J*, the optimal retail price increases with the input of the retailer's BCTS, which may be to compensate for the cost of retailer's BCTS. The producer cuts the wholesale price, then the retailer may order more. At the same time, that may reduce the market demand, resulting in lower revenues for the producer and retailer.

According to (3) of proposition 3, in the case of *J*, with the increase of the UCFI, the market demand decreases. So, the revenues decrease. There is no direct correlation between the two optimal prices and the UCFI. Therefore, investing BCTS can decrease the UCFI and increase the revenues for the fresh supply chain.

D. Decision Model in Case of C

According to formula (11) and (17), we get $p^{H*}-p^{J*} = (a-ec_{or})/4e > 0$. That is, the optimal retail price in case *J* is lower than *H*, but the total revenues are the opposite. Therefore, the fresh supply chain doesn't realize coordination after the BCTS. So, a PDRS contract will be proposed.

The revenues functions of the producer and retailer under the PDRS contract can be expressed as follows.

$$\pi_w^C = w^C D^C + \rho p^C D^C - (c_p+c_s+c_{ow})D^C / \varphi(t^C) \quad (20)$$

$$\pi_r^C = (1-\rho)p^C D^C - (w^C + c_{or})D^C \quad (21)$$

Similarly, by backward induction, the relationship between wholesale price and retail price can be got as $p^{C*} = [e(w^{C*}+c_{or})+a(1-\rho)]/2e(1-\rho)$. If the stakeholders in case *C* want to achieve the total revenues in case *J*, So, the optimal prices under the two models must be $p^{C*} = p^{J*}$. Because the retail price hasn't changed, the demand doesn't change, too. So, $D^{C*} = \theta(t^C)(1-\gamma^C)[\varphi(t^C)(a-ec_{or})-e(c_p+c_s+c_{ow})]/2\varphi(t^C)$. Thus, the optimal decisions of the stakeholders in this mode can be obtained.

$$w^{C*}=\frac{(1-\rho)(c_p+c_s+c_{ow})-\rho c_{or}\varphi(t^C)}{\varphi(t^C)} \tag{22}$$

$$\pi_w^{C*}=\frac{\rho\theta(t^C)(1-\gamma^C)[\varphi(t^C)(a-ec_{or})-e(c_p+c_s+c_{ow})]^2}{4e\varphi(t^C)^2} \tag{23}$$

$$\pi_r^{C*}=\frac{\theta(t^C)(1-\gamma^C)(1-\rho)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]^2}{4e\varphi(t^C)^2} \tag{24}$$

When $\pi_r^{C*}>\pi_r^{H*}$ and $\pi_w^{C*}>\pi_w^{H*}$, the fresh supply chain is coordinated by the PDRS contract, so the conclusion 1 is got.

Conclusion 1: when $\frac{1}{2}<\rho<\frac{3}{4}$, using the PDRS contract can realize the supply chain coordination.

Proof: when $\pi_w^{C*}>\pi_w^{H*}$, $\rho>\frac{1}{2}$; when $\pi_r^{C*}>\pi_r^{H*}$, $\rho<\frac{3}{4}$, so $\frac{1}{2}<\rho<\frac{3}{4}$, conclusion 1 is valid.

Proposition 4:

(1) $\frac{\partial w^{C*}}{\partial c_{ow}}=\frac{1-\rho}{\varphi(t^C)}>0$, $\frac{\partial p^{C*}}{\partial c_{ow}}=\frac{1}{2\varphi(t^C)}>0$,

$\frac{\partial D^{C*}}{\partial c_{ow}}=-\frac{e\theta(t^C)(1-\gamma^C)}{2\varphi(t^C)}<0$,

$\frac{\partial \pi_w^{C*}}{\partial c_{ow}}=-\frac{\rho\theta(t^C)(1-\gamma^C)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]}{2\varphi(t^C)^2}<0$,

$\frac{\partial \pi_r^{C*}}{\partial c_{ow}}=-\frac{\theta(t^C)(1-\gamma^C)(1-\rho)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]}{2\varphi(t^C)^2}<0$.

(2) $\frac{\partial w^{C*}}{\partial c_{or}}=-\rho<0$, $\frac{\partial p^{C*}}{\partial c_{or}}=\frac{1}{2}>0$, $\frac{\partial D^{C*}}{\partial c_{or}}=-\frac{e\theta(t^C)(1-\gamma^C)}{2}<0$,

$\frac{\partial \pi_w^{C*}}{\partial c_{or}}=-\frac{\rho\theta(t^C)(1-\gamma^C)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]}{2\varphi(t^C)}<0$,

$\frac{\partial \pi_r^{C*}}{\partial c_{or}}=-\frac{\theta(t^C)(1-\gamma^C)(1-\rho)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]}{2\varphi(t^C)}<0$.

(3) $\frac{\partial w^{C*}}{\partial \rho}=-\frac{c_{ow}+c_p+c_s+c_{or}\varphi(t^C)}{\varphi(t^C)}<0$, $\frac{\partial p^{C*}}{\partial \rho}=0$, $\frac{\partial D^{C*}}{\partial \rho}=0$,

$\frac{\partial \pi_w^{C*}}{\partial \rho}=\frac{\theta(t^C)(1-\gamma^C)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]^2}{4e\varphi(t^C)^2}>0$,

$\frac{\partial \pi_r^{C*}}{\partial \rho}=-\frac{\theta(t^C)(1-\gamma^C)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]^2}{4e\varphi(t^C)^2}<0$.

(4) $\frac{\partial w^{C*}}{\partial \gamma}=0$, $\frac{\partial p^{C*}}{\partial \gamma}=0$,

$\frac{\partial D^{C*}}{\partial \gamma}=-\frac{\theta(t^C)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]}{2\varphi(t^C)}<0$,

$\frac{\partial \pi_w^{C*}}{\partial \gamma}=-\frac{\rho\theta(t^C)[\varphi(t^C)(a-ec_{or})-e(c_{ow}+c_p+c_s)]^2}{4e\varphi(t^C)^2}<0$.

According to (1) of proposition 4, in the case of *C*, with the increase of producer's BCTS, the two optimal prices increase, but the revenues and demand decrease. It could be that the producer increases its wholesale price to cover the cost of BCTS, forcing the retailer to set a higher retail price. An increase in retail price reduces demand, which decreases the revenues of the producer and retailer.

According to (2) of proposition 4, in the case of *C*, the retailer's BCTS input has a positive impact on the retail price, while the optimal wholesale price and the optimal revenues are opposite. This is probably because the retailer increases the retail price to make up for the cost of the retailer's BCTS. The producer cuts the wholesale price to attract more orders. Nevertheless, higher retail price may reduce the market demand and result in lower revenues for the producer and retailer.

According to (3) of proposition 4, in the case of *C*, the optimal retail price and demand are unaffected by the revenue sharing coefficient. With the increase of revenue sharing coefficient, the wholesale price decreases. This is due to the existence of PDRS contract, in which the retailer gives a percentage of revenues to the producer. In return, the producer cuts wholesale price. The producer gets a certain proportion of revenues sharing, and its revenues increases with the increase of revenue sharing coefficient. The retailer shares a part of its revenues with the producer. So, its revenues will decrease accordingly.

According to (4) of proposition 4, in the case of *C*, the two optimal prices are unaffected by the UCFI. The revenues of producer and retailer is negatively correlated with it. Therefore, investing the BCTS can increase the UCFI and achieve the higher revenues for the fresh supply chain.

V. Numerical Simulation

Numerical simulation is used to verify the properties mentioned above. With reference to Li's [37] research, we select a cherry company in Shandong, China. After the data sorting, the unit cost c_p of cherry is 0.8 ten thousand yuan/ton, and the freight c_s is 1.4 ten thousand yuan/ton. Assuming $a=100t$, $t_0=4$, T=10, γ^Q=0.5$<\gamma^H=\gamma^J=\gamma^C=0.8$, $\varphi(t^i)=1-\lambda(t^i)=2-e_1^{\frac{\ln 2}{T}t^i}$, here, $\lambda(t^i)=e_1^{\frac{\ln 2}{T}t^i}-1$. e_1 is a quantity loss constant. We set $t^Q=4$, $t^H=t^J=t^C=3$. From the research of Li et al. [37], we know $\theta(t^i)=1-\frac{(t^i)^2}{T^2}$. According to the formulas (4)~(24), we get these figures.

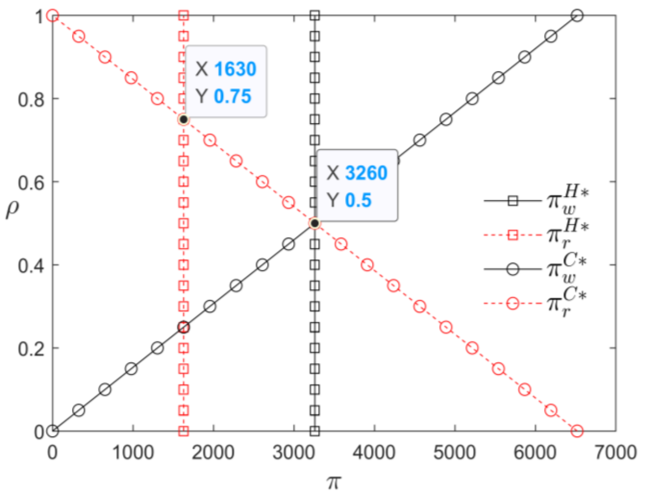

Fig. 2. The relationship between revenues and revenue sharing coefficient

For the figure 2, when $\rho>\frac{1}{2}$, $\pi_w^{C*}>\pi_w^{H*}$. When $\rho<\frac{3}{4}$, $\pi_r^{C*}>\pi_r^{H*}$. That is, when $\frac{1}{2}<\rho<\frac{3}{4}$, the supply chain is coordinated.

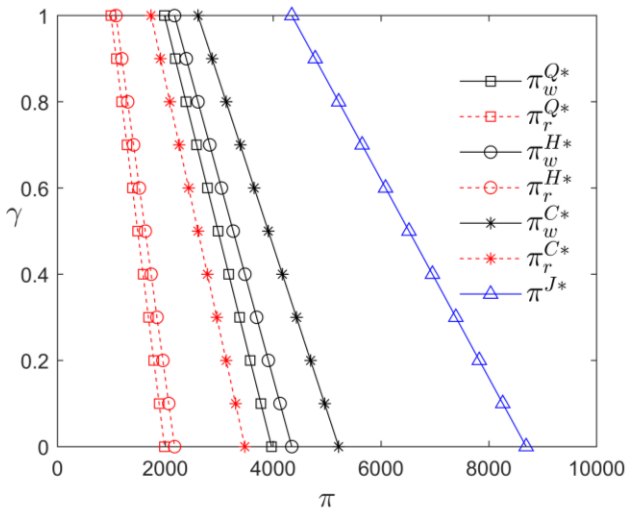

Fig. 3. The relationship between the revenues and the UCFI

For the figure 3, under the same UCFI, the benefits of stakeholders after investing in BCTS are higher than before. Furthermore, stakeholder interests are more sensitive to UCFI after investing in BCTS. This shows that investing in the BCTS can increase the revenues by promoting the UCFI.

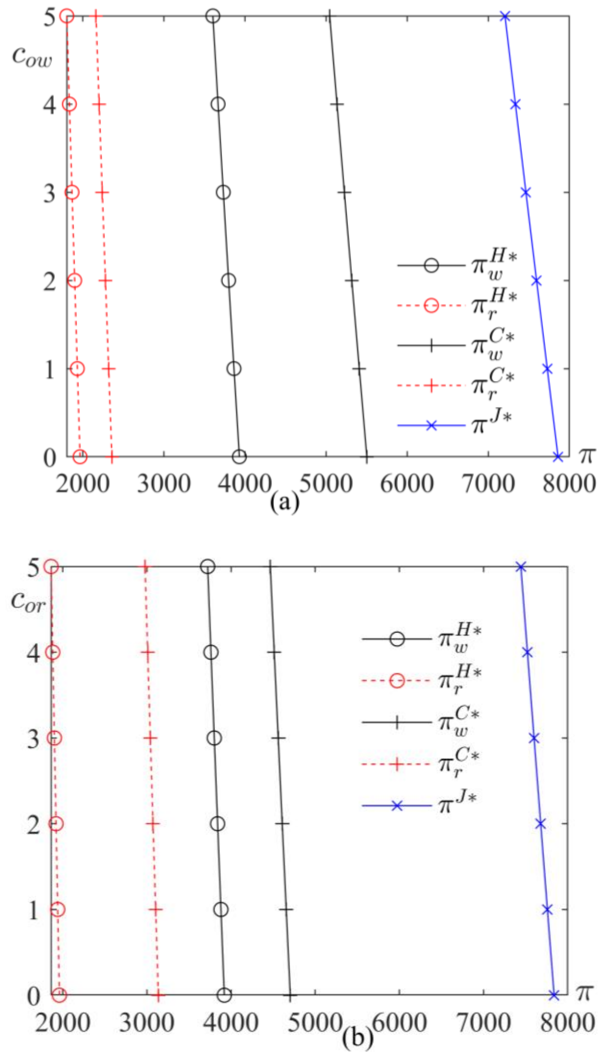

Fig. 4. The relationship between the revenues and unit BCTS cost

For the Figure 4(a), as the producer's BCTS costs increase, the revenues decrease, which is realistic. In the case of the same level of producer cost input in BCTS, the coordination mode can increase the revenues of supply chain members more. Therefore, if supply chain members want to invest in BCTS to achieve higher revenues, they need to coordinate the supply chain by using some incentive policies.

For the Figure 4(b), the revenues will decrease as the retailer's BCTS cost increases. The revenues of the producer and retailer has different sensitivities to the impact of the BCTS at different levels of revenue sharing coefficient. When the supply chain decision-makers want to reach their own expected revenues, they should put forward some price reciprocal policies in the negotiation to coordinate the fresh supply chain and promote the revenues.

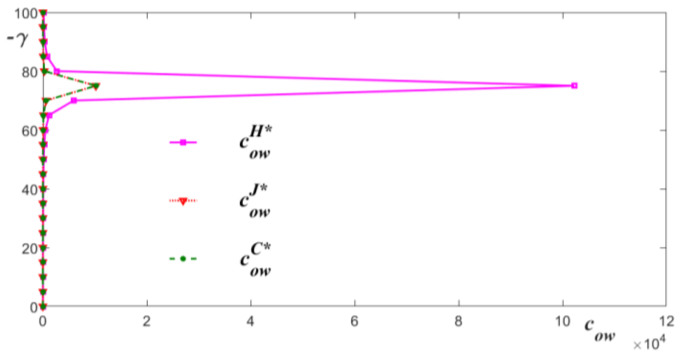

Fig. 5. The relationship between the UCFI and the producer's BCTS cost

For the Figure 5, the UCFI is negatively correlated with the producer's unit BCTS cost. In the coordination mode, the UCFI is more closely related to the producer's BCTS cost. The sensitivity of UCFI varies within the range of different producers' unit BCTS costs. Therefore, producers should find key investment horizons if they want to get less UCFI with less input.

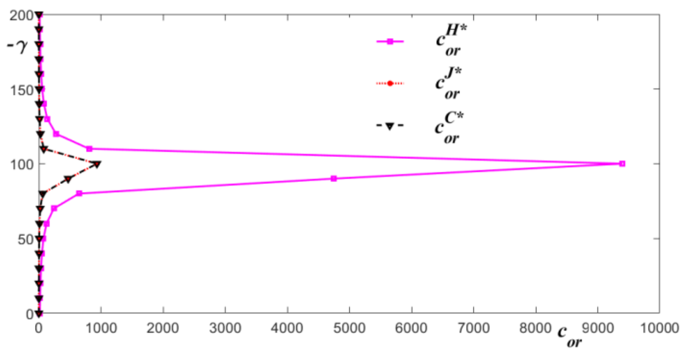

Fig. 6. The relationship between the UCFI and the retailer's BCTS cost

For the Figure 6, the UCFI is negatively correlated with the cost of retailer's unit BCTS. In coordination mode, it has a greater relationship with the retailer's unit BCTS cost. Compared with Figure 5, it is more sensitive than the producer's investment. Therefore, when making investment decisions, the retailer can appropriately increase the level of investment in BCTS. The sensitivity of the UCFI varies within the range of different retailer's unit BCTS cost. Therefore, if the retailer wants to obtain fewer UCFI with the less investment, it should identify the key investment interval.

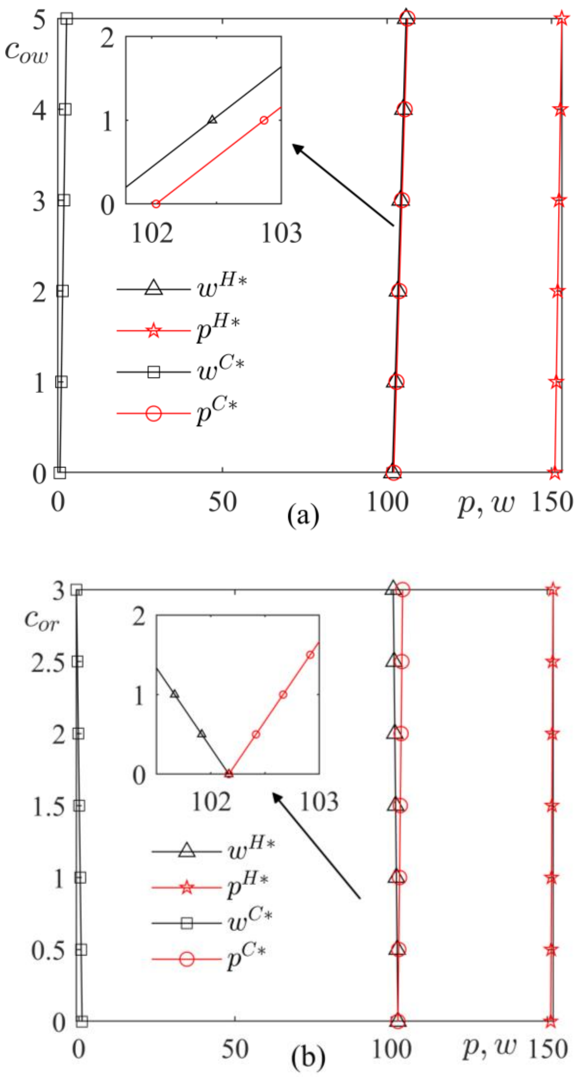

Fig. 7. The relationship between the price and unit BCTS cost

For the Figure 7(a), the producer's unit BCTS cost has a positive effect on the two optimal prices. It suggests that the producer improves the wholesale price to cover the cost of investing in BCTS, while the retailer raises the retail price to offset the increased wholesale cost. This also demonstrates that the coordination model can decrease the two optimal prices in the fresh supply chain.

For the Figure 7(b), the retailer's unit BCTS cost has a positive effect on the optimal retail price, but the optimal wholesale price has the opposite effect. This suggests that when members of the fresh supply chain want to invest in BCTS to achieve product information symmetry and improve yields, the producer will give the retailer appropriate preferences, such as the low wholesale price. The retailer may raise the retail price to cover the cost of BCTS. This also demonstrates that the coordination model can decrease the two optimal prices in the fresh supply chain.

As we can see in Figure 8, there is no direct correlation between the two optimal prices and the UCFI under the four decision modes. In other words, under the same condition, the UCFI doesn't affect the formation of the two optimal prices. So, the stakeholders can improve its revenues by affecting UCFI when pricing.

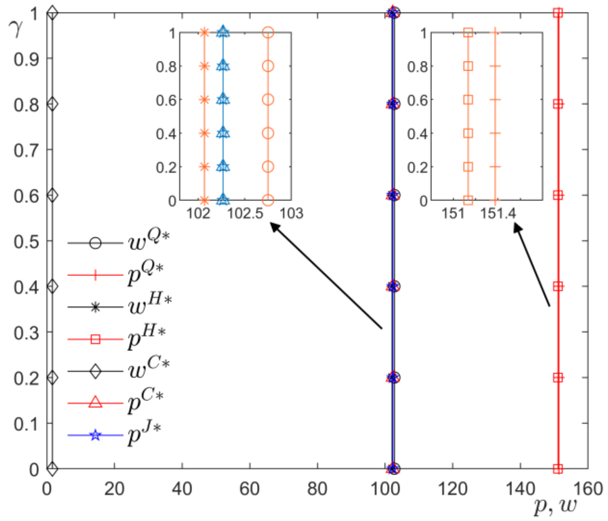

Fig. 8. The relationship between the price and the UCFI

VI. Discussions

In this section, we will compare the conclusions of this paper with previous studies to highlight our efforts.

(1) This study enriches the application background of blockchain, and puts forward the investment decision of fresh supply chain after investing in blockchain technology from the perspective of freshness information unreliability. Although, Wu et al. [29] studied the impact of blockchain technology on fresh supply chain investment strategies, they did not consider the level of consumer freshness information unreliability.

(2) Compared with Cai et al. [35], this paper still uses the multiplication rule to integrate the freshness information unreliability into the demand function, which expands the application scope of the demand function. However, we mainly study the impact of freshness information unreliability on the investment decision of fresh supply chain, which is different from its research purpose.

(3) This paper found that investing in BCTS can improve the retail price of fresh products, which is similar to the research results of Sun et al. [31] and Lin et al. [33], but the investment threshold is different, which may be due to the different research backgrounds. After investing in BCTS, the CSPD contract can coordinate the fresh supply chain, which is similar to the research results of Liu et al. [30], and expands the application scope of the contract.

VII. Conclusions

In this paper, we analyzed the revenues of the fresh supply chain in both independent and centralized decision-making modes considering the freshness information unreliability and the BCTS input. The fresh supply chain was coordinated using the PDRS contract, and the optimal decision-making changes of supply chain members under different BCTS investment conditions were discussed. The following conclusions were obtained:

(1) The producer and retailer investing in BCTS can increase their revenues. However, as the investment costs increase, their revenues will decrease, decision makers need to grasp the investment cost threshold and develop some reciprocal contracts to increase fresh stakeholders' revenues.

(2) Investing in BCTS can effectively reduce the unreliability coefficients of freshness information and improve the purchase rate of consumers. When the unreliability coefficients of freshness information are the same, investing in BCTS can improve the revenues of the fresh supply chain. Moreover, what the retailer spends on BCTS costs is more effective in reducing UCFI. Therefore, some preferential policies can be set for the retailer to encourage it to invest in BCTS so as to increase the fresh stakeholders' revenues.

(3) When $\frac{1}{2} < \rho < \frac{3}{4}$, adopting the PDRS contract can stimulate the enthusiasm of producer and retailer and realize the fresh supply chain coordination.

(4) There is no direct correlation between the two optimal prices and the UCFI. The stakeholders can improve revenues by influencing the UCFI.

The next step is to study the pricing rules of multi-stage fresh supply chain and dual-channel fresh supply chain considering the application of blockchain traceability service technology and the unreliability coefficients of freshness information.

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