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Supply chain coordination of fresh Agri-products based on value loss

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Abstract
Agricultural products are easy to deteriorate in long-distance transportation. Excessive circulation loss not only increases the cost of fresh agri-product supply chain, but also damages the safety and quantity of fresh agri-products. The value loss of fresh agri-products under different transportation modes was studied. This paper analyzes the conditions for the supplier to choose normal temperature transportation and cold chain transportation, and the influence of different transportation modes on the retailer's decision. The value loss of fresh agri-products under different transportation modes was studied. The conditions of choosing normal temperature transportation or cold chain transportation and the influence of different transportation modes on the retailer's decision are analyzed. It is found that when the supplier chooses cold chain transportation, the retailer and the whole supply chain can get more profits. The retailer is encouraged to make appropriate supply chain contracts with the supplier, such as the improved revenue-sharing contract or the cost-sharing contract, and the supplier is encouraged to adopt cold chain transportation mode to improve the utilization rate of cold chain transportation of fresh agri-products. Consumers' sensitivity to freshness has a great impact on the strategies of supply chain members. The contribution of this work also includes reducing the circulation loss of agri-products and providing guidance for the operation and management of agri-products enterprises.

Keywords Value loss · Fresh Agri-products · Supply chain coordination · Cost-sharing contract · Improved revenue-sharing contract

1 Introduction

Fresh agri-products such as vegetables, fruits, and milk have obvious seasonal characteristics, shorter life cycles, and complex supply and demand situation compared with other perishable products. Due to the long distance between production places and target markets, their unique natural attributes make them vulnerable to damage during transportation, which inevitably leads to the loss of quantity and freshness. In this paper, two types of loss are called value loss. Quantity loss reflects the deterioration of some products in the long-distance transportation, resulting in the quantity of agri-products arriving at the retailer less than the order quantity of the retailer. The freshness of agri-products has a direct impact on their quality and consumers' purchasing behavior. According to statistics, the loss rate of fresh agri-products in China is 20%–30%, with an annual loss of about 80 million tons. In developed countries, the loss rate is only 1.7% to 5% (Agronet 2013). Such a huge difference lies in the lack of mature and advanced cold chain logistics system. In order to improve the freshness of agri-products and effectively reduce the quantity loss rate in the precess of long-distance transportation, cold-chain logistics can be adopted.

With the development of social economy and the improvement of People's living standard, people pay more and more attention to cold-chain transportation, which can keep the original color, freshness, and nutritional value of fresh agri-products. Cold-chain transportation also meets the quality and safety requirements of the consumer market. Moreover, it plays an important role in maintaining the value and reducing the circulation loss of fresh agri-products. In China, it is reported that only 15% of fresh agri-products are transported under refrigerated conditions although such food need to be refrigerated (Cai 2019). How to increase the utilization rate of cold-chain system is an important challenge due to the

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inherent attributes of agri-products. In addition, the cold-chain logistics from the supplier to the retailer is the first step and also a crucial step in the supply chain. Especially for the retailer connecting the producer and the market, the front-end cold-chain logistics adopted by the supplier can extend the sales period of products (it is reported that fresh flowers can last up to 7–10 days if the cold-chain system is adopted (Hua 2016). Meanwhile, fresh food with high freshness is more popular with customers.

Some documents consider the freshness-keeping effort of the retailer or the third-party logistics service provider. However, on the one hand, they don't quantify the freshness-keeping effort as a daily operational strategy; on the other hand, they also don't consider its impact on the decisions of other players, such as changing the shelf-life of products. Many incentive schemes are studied in the decentralized system. They don't investigate the motivation of supply chain members to make coordinated decisions. In this paper, the motivation of the follower is considered in the game model to encourage the supplier to adopt the incentive contract, and the effectiveness of two common contracts is tested. Considering the impact of front-end cold-chain logistics on the whole supply chain, how will the supplier determine the logistics mode? How will the logistics mode affect the retailer's decision? How should the retailer response to the supplier's logistics mode to maximize profits? Can the supply chain members be motivated to make coordinated decisions so as to optimize the performance of the whole supply chain and benefit everyone? This paper will discuss these problems.

The remainder of the paper is organized as follows. In Section 2, we briefly review the relevant literature. The problem formulation, assumptions, and notation are presented in Section 3. In Section 4, we give the optimal decisions of the supply chain under the cold-chain logistics and normal temperature logistics. In Section 5, we propose two incentive schemes: the cold-chain cost-sharing contract and the improved revenue-sharing contract, and find that the improved revenue-sharing contract can coordinate the supply chain and make the profit of the supply chain members reach the optimal. Section 6 provides the numerical examples and managerial implications, Followed by the conclusions in Section 7.

2 Literature review

This study involves the following two research directions. One is the supply chain management of perishable products, the other is the supply chain coordination contract.

2.1 Supply chain management of perishable products

There are abundant literatures on supply chain management of fresh agri-products. More research papers on this issue focus on deteriorating inventory models. The EOQ model of perishable goods was developed in a deterministic environment where the demand rate decreases linearly with the age of the product, they took into account the freshness loss of perishable goods (Dobson et al. 2017). Similarly, in the model, the deterministic demand depends on the product's residual life (Demirag et al. 2017). Chen et al. (2019) proposed an algorithm for this complex situation in which inventory has a random lifetime and demand is deterministic, inventory level dependent, time-varying, and price dependent. In the aspect of inventory control of perishable goods, some studies have been done in pricing and ordering. Banerjee and Agrawal (2017) focused on the change of inventory value caused by freshness loss and provided the optimal discounting policy. Mattsson (2010) extended the reorder point considering the seasonal demand. Bahroun and Belgacem (2019) determined dynamic safety stock levels under cyclic production schedules. Bai et al. (2016) considered a one-manufacturer-one-retailer supply chain for deteriorating items and assumed that the demand is sensitive to the selling price, the time, and the retailer's effort. Ghoreishi et al. (2014) solved the joint pricing and inventory control model for non-instantaneous deteriorating items, taking into account the time value of money and customer returns, the demand depends on time and price.

Generally speaking, the above studies only consider the quality loss or quantity loss of perishable goods. In practice, fresh produces such as vegetables, fruits and milk are characterized by quantity loss and quality loss. Only several articles focus on two types of loss. In the model proposed by Qin et al. (2014), quantity loss and quality loss occurred simultaneously, and the demand rate was assumed to be deterministic and depended on the product's quality, selling price and on-display stock level. They found the optimal joint price and inventory strategy. Cai et al. (2013) and Wu et al. (2015) characterized equilibrium decisions of a fresh produce supply chain with freshness-keeping service provided by a third-party logistics (3PL) provider. Based on their model, Yu and Xiao (2017) assumed that the cold-chain service provided by the 3PL provider affected quantity loss and quality loss, and tested the impact of channel leadership. In addition, Ma et al. (2019) integrated demand information asymmetry and perishability in a three-echelon fresh agri-product supply chain.

Cold chain transportation is one of the direct ways of freshness-keeping service. Meanwhile, some papers focus on the use of cold chain transportation to reduce value loss. James et al. (2006) studied the impact of cold chain transportation on food quality and improved the system model previously studied. In terms of food safety, Likar and Jevšnik (2006) analyzed the loss caused by the lack of attention and importance of supply chain members to cold chain transportation. Yue et al. (2013) analyzed that the shelf life of the aquatic products can be extended by adjusting the temperature of the cold chain.

To sum up, quantity loss and quality loss are always ignored in most models for fresh products. However, both of them play an important role in influencing demand. Therefore, in this paper, we assume that both quantity loss and quality loss are endogenous variables, and combine cold-chain logistics with two types of loss. We take the lead in investigating the supplier's freshness-keeping decision, and can decide whether to adopt cold-chain logistics. It's more realistic to quantify the freshness-keeping effort in this way. What's more, this paper investigates the impact of the front-end logistics mode on the whole supply chain.

2.2 Supply chain coordination contract

Research on supply chain coordinated contracts for perishable products is another related research direction. In order to eliminate double marginalization, control risks and improve performance, a lot of contracts have been proposed, including the buy-back contract (Chen and Bell, 2011; Wu, 2013), the quantity discount contract (Plambeck and Taylor 2005; Venegas and Ventura 2018), the wholesale price contract (Xu and Bisi, 2012), and the revenue-sharing contract (Xiao and Xu 2013). However, the buy-back contract and the quantity discount contract can encourage the retailer to purchase more products to some extent. Fresh foods have the characteristic of shorter life cycle and perishable, and the retailer has to bear greater inventory risk, so these two contracts are not suitable for fresh produce supply chain. Although the wholesale price contract is simple, widespread use shows its effectiveness. Hwang et al. (2018) pointed out the clear measurement of the performance of the wholesale price contract and its effect on inducing reliable supply. Another interesting finding of Hou et al. (2017) was that the performance of the supply chain with the leader-follower game can be improved through the wholesale price contract rather than the revenue-sharing contract. The wholesale price contract is applied by the leader of the supply chain to encourage downstream enterprises to increase orders. In this paper, the follower has the motivation to encourage the supplier to adopt the coordination strategy. Therefore, wholesale price contract isn't applicable to our model.

In the revenue sharing strategy, apart from the wholesale price, the retailer gives the manufacturer a fixed percentage of its revenue from the market. Bai et al. (2015) proposed a revenue-sharing contract for deteriorating items in a two-echelon supply chain composed of one manufacturer and one retailer, and verified the coordination of the revenue-sharing contract. Hou et al. (2017) found the revenue-sharing contract can coordinate the decentralized supply chain with the simultaneous-move game. The cost-sharing contract refers to the supply chain members sharing the cost of products or services in the supply chain to ensure the quality and quantity of products. The cost-sharing contract is a common contact considering the freshness-keeping effort in the agri-product supply chain, such as Song and He (2019). These models only design contracts to coordinate the decentralized system rather than check the effectiveness of several applicable contracts.

In the field of fresh agri-products, there are a large number of small and medium-sized retailers, and there is no contract between suppliers and retailers. The revenue-sharing contract and cost-sharing contract are easy to implement and win-win for all participants. Therefore, this paper introduces the cost-sharing contract and improved revenue-sharing contract, and tests their effectiveness.

The main contributions of our work are as follows. First, our model takes into account the quantity loss and quality loss of fresh products: the quantity loss affects the number of products arrived at the market. In addition, we consider the customer utility related to the price and quality of products. Second, there is a sharp contrast with the literature on freshness-keeping effort. In order to control the value loss, we study the transportation decision of the supplier, which has never been studied before. In addition, we investigate the effect of the front-end logistics of the supplier. Thirdly, we establish a model to compare and analyze the optimal decisions of cold-chain logistics and normal temperature logistics. Lastly, when the supplier chooses normal temperature logistics, the motivation of the retailer to encourage the supplier to choose cold-chain logistics is studied, and two contracts are designed to coordinate the supply chain. We find an improved revenue-sharing contract can maximize the profits of the supplier and the retailer compared with the cold-chain logistics without contracts. In contrast, the cost-sharing contract is invalid.

3 Problem description and assumptions

In this work, the fresh agri-product supply chain is simplified as "supplier + retailer + consumer" to form a three-echelon supply chain. Its structure is illustrated in Fig. 1.

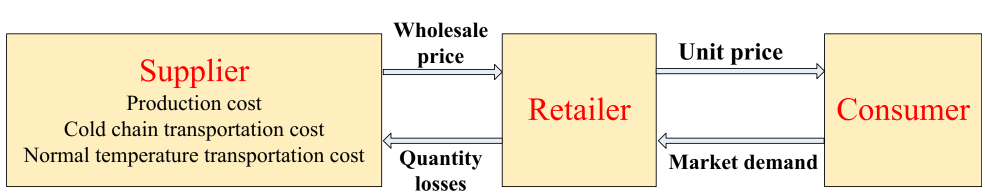


Fig. 1 Circulation process of fresh agri-product supply chain

We are concerned about the timeline of events. The supplier delivers a batch of fresh agri-products transported at normal temperature or cold chain to the target market. The mode of transportation will affect the freshness and quantity of agri-products reaching the target market. The supplier bears the transportation cost and the loss of deterioration of agri-products during long-distance transportation. The supplier sets the wholesale price according to the mode of transportation and value loss. After the fresh agri-products come into the market, the retailer determines the retail price according to the freshness of the agri-products.

Agricultural products will inevitably deteriorate in the process of long-distance transportation, resulting in the loss of quality and the surviving quantity. We model the time-dependent function as the freshness index:

$$\theta_i(t) = \theta_i - \eta\left(\frac{t}{T_i}\right)^2 \qquad t \in [0, T_i] \tag{1}$$

$\theta_i(t)$ is in the range of [0, 1], where $\theta_i(t) = 1$ and $\theta_i(t) = 0$ represent "completely fresh" and "completely deteriorated" products, respectively. θ_i is the freshness of agri-products on the market. Products arriving at the retailer are fresher under cold chain transportation. T_i is the sales period of agri-products. According to Yue et al. (2013), cold-chain service can extend the shelf life of products, therefore, we assume the sales period of fresh products under cold-chain transportation is longer than that of normal temperature transportation. Furthermore, η is the extreme value of the deterioration rate of agri-products, which means that the freshness of agri-products will decrease at the end of the sale period.

Freshness is an external indicator of the quality of fresh products, which affects consumers' purchasing behavior. The retail price is another focus for consumers. Therefore, consumers actually determine their purchase behavior by judging the impact of freshness and the price of fresh agri-products on their own utility. Similar to Xu and Bisi (2012), the utility function of agri-products is as follows:

$$U_i(t) = \mathrm{u} + \alpha\theta_i(t) - \beta P_i \tag{2}$$

Where urepresents the initial value of fresh products and follows the uniform distribution of [0, 1], α denotes consumers' sensitivity to freshness of products, and β denotes consumers' sensitivity to the product price.

The assumptions in the model are as follows:

(1) The transportation time is equal under two transportation modes;
(2) The surplus value of fresh agri-products after the end of the life cycle is 0, and the shortage is negligible;
(3) In the sale period T_i, the retailer can sell out all products, and the potential consumer market of the product λ is constant;
(4) The supplier and the retailer are risk neutral, so they make decisions for their maximum profit.

The related notations used are listed in Table 1.

4 Effect of value loss on fresh Agri-product supply chain without coordinating contract

When the utility function is positive, consumers decide to purchase fresh agri-products, that is, $U_i(t) > 0$; otherwise, the consumer will give up the purchase. According to Assumption (3), the market demand for fresh products at any time t is:

$$\begin{aligned} D_i(t) &= \lambda P(\mathrm{u} + \alpha\theta_i(t) - \beta P_i > 0) \\ &= \lambda P\left(\mathrm{u} + \alpha\left(\theta_i - \eta\left(\frac{t}{T_i}\right)^2\right) - \beta P_i > 0\right) \\ &= \lambda\left(1 - \beta P_i + \alpha\left(\theta_i - \eta\left(\frac{t}{T_i}\right)^2\right)\right) \end{aligned} \tag{3}$$

Therefore, during the sales period T_i, the overall order quantity of agri-product supply chain is:

$$Q_i = \int_0^{T_i} D_i(t)dt = \int_0^{T_i} \lambda\left(1 - \beta P_i + \alpha\left(\theta_i - \eta\left(\frac{t}{T_i}\right)^2\right)\right)dt \tag{4}$$

The retailer's profit is:

$$\begin{aligned} \prod_{ri} &= (p_i - w_i)Q_i \\ &= (p_i - w_i)\int_0^{T_i} \lambda\left(1 - \beta P_i + \alpha\left(\theta_i - \eta\left(\frac{t}{T_i}\right)^2\right)\right)dt \end{aligned} \tag{5}$$

From Eq. (5), we can obtain the optimal retail price:

Lemma 1 For any given the supplier's wholesale pricew_i, the optimal retail price is$P_i^*(w_i) = \frac{3+3\alpha\theta_i - \alpha\eta + 3w_i\beta}{6\beta}$. Therefore, the optimal order quantity is$Q_i^*(w_i) = \frac{\lambda T_i(3+3\alpha\theta_i - \alpha\eta - 3w_i\beta)}{6}$.

The profit function of the fresh product supplier is:

$$\begin{aligned} \prod_{si} &= w_i Q_i - (c_m + c_i)\frac{Q_i}{\phi_i} \\ &= \left(w_i - \frac{c_m + c_i}{\phi_i}\right)\int_0^{T_i} \lambda\left(1 - \beta P_i + \alpha\left(\theta_i - \eta\left(\frac{t}{T_i}\right)^2\right)\right)dt \end{aligned} \tag{6}$$

Substituting $P_i^*(w_i)$ and $Q_i^*(w_i)$ into Eq. (6), we obtain the optimal supplier's profit. The profit function has a decision variable w_i:

Lemma 2 The optimal wholesale price of the fresh product supplier is $w_i^* = \phi_i \frac{M_i + 3C_i}{6\beta\phi_i}$, where$M_i = 3 + 3\alpha\theta_i - \alpha\eta$,$C_i = \beta(c_m + c_i)$.

Table 1 Notations

Parameters	Symbol	Description
	Subscript n	The transportation mode; $n = s$, t respectively represents normal temperature transportation or cold chain transportation
	c_m	The unit production cost of the supplier
	c_n	The logistics cost of unit product under different transportation modes; $c_t > c_s$
	ϕ_n	The number of quantity losses, $\phi_t < \phi_s$
	$\theta_i(t)$	The freshness of the product at time t in the sales period
	θ_i	The freshness of the product reaching the retailer; $\theta_t > \theta_s$
	T_i	The sales period of the product; $T_t > T_s$
	λ	The potential consumer market
	$\prod_{rn}$	The profit of the retailer in the decentralized supply chain
	$\prod_{sn}$	The profit of the supplier in the decentralized supply chain
	Superscript "*"	Optimal result
	Superscript "1"	The optimal decision under a wholesale price contract
	Superscript "2"	The optimal decision under an improved revenue-sharing contract
Decision variables	w_n	The wholesale price of the supplier
	p_n	The selling price of unit product
	Q_n	The retailer's order quantity
	ε	The revenue-sharing ratio
	μ	The cost-sharing coefficient
	δ	The supplier's transfer fee

The calculation of w_i^* means that the wholesale price will increase with the increase of product value and unit product logistics cost. For fresher products, the supplier will set a higher wholesale price. The greater the quantity loss, the less effective supply, and the higher the wholesale price.

Lemma 2 gives an optimal wholesale price. By substituting w_i^* into Lemma 1, we get the optimal retail price $P_i^* = \phi_i \frac{M_i+C_i}{4\beta\phi_i}$ and the optimal order quantity $Q_i^* = \lambda T_i(\phi_i \frac{M_i-3C_i)}{12\phi_i}$, where $\phi_i M_i - 3C_i > 0$.

Some parameters have the same effect on the retail price and the wholesale price. Due to the loss of quality and quantity, the selling price is lower. The order quantity mainly depends on the sales period, the product value and the logistics cost per unit product. If the sales period of the product is longer, the retailer will order more products for sale. Controlling quantity and quality loss means increasing logistics cost. Therefore, the retailer should balance the increase of wholesale price and the increase of logistics cost (such as longer sales period and fresher agri-products) when decides to order products.

By substituting w_i^*, P_i^* and Q_i^* into Eqs. (5) and (6), the optimal profits of the retailer and the supplier are obtained as follows:

$$\prod_{ri}^* = \frac{\lambda T_i(\phi_i M_i - 3C_i)^2}{48\beta\phi_i^2} \tag{7}$$

$$\prod_{si}^* = \frac{\lambda T_i(\phi_i M_i - 3C_i)^2}{24\beta\phi_i^2} \tag{8}$$

We can find $\frac{\prod_{si}^*}{\prod_{ri}^*} = 2$ in two transportation modes, which is related to the buyer's market. The Stackelberg game model in this paper is a leader-follower game. As a leader, the supplier gains more profits than the follower.

4.1 Comparative analysis of two value loss models

We can obtain Theorem 1 by comparing the optimal retail price, optimal wholesale price and profit of the supply chain under cold-chain transportation and normal temperature transportation:

Theorem 1: (1)$w_t^* > w_s^*$, $P_t^* > P_s^*$.

(2) When $0 < T_s\phi_t(\phi_s M_s - 3C_s) < T_t\phi_s(\phi_t M_t - 3C_t)$, $Q_t^* > Q_s^*$; otherwise, $Q_t^* < Q_s^*$;

(3) When $T_t\phi_s^2(\phi_t M_t - 3C_t)^2 > T_s\phi_t^2(\phi_s M_s - 3C_s)^2$, $\prod_{rt}^* > \prod_{rs}^*$, $\prod_{st}^* > \prod_{ss}^*$.

Theorem 1 indicates that cold-chain transportation helps the supplier and the retailer to set higher wholesale price and retail price. Firstly, customers intend to buy fresher products; Secondly, cold chain can sharply reduce value loss, in the meanwhile, the supplier has to bear higher logistics cost. As a result, these factors lead to price increases. Under certain conditions, the order quantity and the profit of supply chain members are higher under cold-chain transportation, which is an interesting conclusion. The retailer doesn't order more products just because they can sell longer.

Theorem 2: When $c_t \leq C^R_{T\max}$ or $c_t \geq C^R_{T\min}$, where C^R_T is the threshold of cold-chain logistics cost, the supplier chooses cold-chain transportation in the decentralized supply chain.

When $\prod^*_{ss} = \prod^*_{st}$, we can obtain $C^R_{T\min} = \varphi_t M_t + \sqrt{\frac{T_s}{T_t}} T_t * \varphi_t(\varphi_s \frac{M_s - 3C_s)}{\frac{\varphi_s}{3\beta - c_m}}$, $C^R_{T\max} = \varphi_t M_t - \sqrt{\frac{T_s}{T_t}} T_t * \varphi_t(\varphi_s \frac{M_s - 3C_s)}{\frac{\varphi_s}{3\beta - c_m}}$. When $c_t \leq C^R_{T\max}$ or $c_t \geq C^R_{T\min}$, the supplier's profit is higher under cold-chain transportation, so the cold-chain transportation is chosen in the fresh agri-product supply chain. In this case, the retailer's profit also increases, which means that the retailer can also benefit from the cold-chain transportation. Therefore, the retailer wants the supplier to choose cold-chain transportation. To sum up, the profit of each member of the supply chain will increases if the supplier chooses cold-chain transportation, especially when the cost of cold-chain logistics is within a certain range.

5 Incentive schemes to induce coordination

When the cost of cold-chain logistics exceeds a certain range, the supplier will choose normal temperature transportation, so supply chain members cannot get the maximum profit. It is necessary to design a contract to make the profit of supply chain members under cold-chain transportation higher than that under normal temperature transportation. We will examine whether the cost-sharing contract and the improved revenue-sharing contract are effective in coordinating the supply chain.

5.1 Optimal decisions under the cost-sharing contract

The cost-sharing contract includes two parameters, one is the wholesale price w^1_t, the other is the retailer's cost-sharing coefficient expressed by $\mu(0 < \mu < 1)$.

The retailer's profit under cold-chain transportation in the cost-sharing contract is:

$$\prod^1_{rt} = \left(p_t - w_t - \frac{\mu c_t}{\phi_t}\right) Q_t = \left(p_t - w_t - \frac{\mu c_t}{\phi_t}\right) \int_0^{T_t} \lambda \left(1 - \beta P_t + \alpha \left(\theta_t - \eta \left(\frac{t}{T_t}\right)^2\right)\right) dt \quad (9)$$

The profit function of the supplier is:

$$\prod^1_{st} = w_t Q_t - [c_m + (1-\mu) c_t] \frac{Q_t}{\phi_t} = \left[w_t - \frac{c_m + (1-\mu) c_t}{\phi_t}\right] \int_0^{T_t} \lambda \left(1 - \beta P_t + \alpha \left(\theta_t - \eta \left(\frac{t}{T_t}\right)^2\right)\right) dt \quad (10)$$

Based on the above, Theorem 3 is obtained.

Theorem 3: Under the cost-sharing contract, for any given the cost-sharing coefficient μ, the optimal wholesale price is $w^1_t = \phi_t \frac{M_t + 3\beta c_m + 3\beta(1-2\mu)c_t}{6\beta\phi_t}$, the optimal retail price is $P^1_t = \phi_t \frac{M_t + \beta C_t}{4\beta\phi_t}$, and the optimal order quantity is $Q^1_t = \lambda T_i(\phi_t \frac{M_t - 3C_t)}{12\phi_t}$.

Theorem 3 gives the optimal decision of supply chain. Compared with the supply chain without contract under cold-chain transportation, the wholesale price is lower because the retailer shares part of the logistics cost. But surprisingly, $P^1_t = P^*_t$, $Q^1_t = Q^*_t$, which means that cost sharing has no effect on the optimal retail price and order quantity. From the retailer's point of view, the profit from lower wholesale price is equal to the logistics cost it bears. Therefore, the retailer's sale price and order quantity remain unchanged under the cost-sharing contract.

By substituting w^1_t, P^1_t and Q^1_t into Eqs. (9) and (10), the optimal profits of the retailer and the supplier are as follows:

$$\prod^1_{rt} = \prod^*_{rt} = \frac{\lambda T_t (\phi_t M_t - 3C_t)^2}{48\beta\phi_t^2} \quad (11)$$

$$\prod^1_{st} = \prod^*_{st} = \frac{\lambda T_t (\phi_t M_t - 3C_t)^2}{24\beta\phi_t^2} \quad (12)$$

It can be seen from Eqs. (11) and (12) that under cold-chain transportation, the profits of the retailer and the supplier are the same as those without contract. For the supplier, Although the logistics cost is reduced, the wholesale price is still falling, so its profit remains unchanged. From the retailer's point of view, the profit from lower wholesale price is equal to the logistics cost it bears. According to Theorem 2, when $c_t > C^R_T$, the supplier gets less profit from cold-chain transportation. In other words, compared with the normal temperature transportation without contract, the retailer and the supplier don't get more profits under the cost-sharing contract. Therefore, the supplier will not choose the cold-chain transportation mode, and the cost-sharing contract can't coordinate the supply chain.

5.2 Optimal decisions under improved revenue-sharing contract

When the supplier chooses normal temperature transportation mode, we design a case in which the retailer shares part of the revenue with the supplier to encourage the supplier to choose cold-chain transportation. However, the supplier is a leader in the game and earns more profits than the retailer, so the supplier transfers δ to the retailer at the end of the sales to achieve a win-win situation. When the supplier chooses the cold-chain transportation under the improved revenue-sharing contract, the retailer and the supplier can get more profits than the normal temperature transportation, The improved revenue-sharing contract includes the wholesale price w_t^{2}, the retailer's revenue-sharing ratio expressed by $\varepsilon(0 < \varepsilon < 1)$, and the supplier's transfer fee represented by δ. According to the above descriptions, we get the profit function of the retailer as follows:

$$\prod\nolimits_{rt}^{2} = (\varepsilon p_t - w_t)Q_t + \delta$$
$$= (\varepsilon p_t - w_t)\int_0^{T_t}\lambda\left(1-\beta P_t + \alpha\left(\theta_t - \eta\left(\frac{t}{T_t}\right)^2\right)\right)dt + \delta \quad (13)$$

Then, the profit function of the supplier is:

$$\prod\nolimits_{st}^{2} = \left(w_t - \frac{c_m + c_t}{\phi_t}\right)Q_t + (1-\varepsilon)p_t Q_t - \delta$$
$$= \left[w_t - \frac{c_m + c_t}{\phi_t} + (1-\varepsilon)p_t\right]\int_0^{T_t}\lambda\left(1-\beta P_t + \alpha\left(\theta_t - \eta\left(\frac{t}{T_t}\right)^2\right)\right)dt - \delta \quad (14)$$

Based on the above, Theorem 4 is obtained.

Theorem 4: Under the improved revenue-sharing contract, for any given revenue-sharing ratio ε, the optimal wholesale price is $w_t^2 = \varepsilon\phi_t(3\varepsilon + 3\varepsilon\alpha\theta_t)\frac{+3\varepsilon C_t - \alpha\eta\phi_t}{3\beta(1+\varepsilon)\phi_t}$, the optimal retail price is $P_t^2 = (1+2\varepsilon)\phi_t(3\varepsilon + 3\varepsilon\alpha\theta_t)\frac{+3\varepsilon C_t - \alpha\eta\phi_t(\varepsilon^2+\varepsilon+1)}{6\varepsilon\beta(1+\varepsilon)\phi_t}$, and the optimal order quantity is $Q_t^2 = \lambda T_t[\phi_t(3\varepsilon + 3\varepsilon\alpha\theta_t)$ $\frac{-3\varepsilon C_t + \alpha\eta\phi_t(\varepsilon^2-\varepsilon-1)]}{6\varepsilon(1+\varepsilon)\phi_t}$.

According to Theorem 4, the optimal decision of supply chain is related to revenue-sharing ratio, consumers' sensitivity to the freshness, the freshness of products and quantity loss.

Substituting into Eq. (13) and (14), we obtain the optimal profit of the retailer and the supplier as follows:

$$\prod\nolimits_{rt}^{2} = \frac{\lambda T_t\left[\left(K_t - (\varepsilon^2+\varepsilon-1)D_t\right][K_t + (\varepsilon^2-\varepsilon-1)D_t]\right.}{36\varepsilon\beta\phi_t^{2}(1+\varepsilon)^2} + \delta \quad (15)$$

$$\prod\nolimits_{st}^{2} = \frac{\lambda T_t[K_t + (\varepsilon^2-\varepsilon-1)D_t]^2}{36\varepsilon^2\beta\phi_t^{2}(1+\varepsilon)} - \delta \quad (16)$$

$K_i = \phi_i(3\varepsilon + 3\varepsilon\alpha\theta_i) - 3\varepsilon C_i D_i = \alpha\phi_i\eta$

Under the following conditions, we can obtain Theorem 5.

Theorem 5: When the revenue-sharing ratio satisfies $0 < 3\lambda T_s(K_s - \varepsilon D_s)\frac{2}{\phi_s^{2} < \min\{B_1}, B_2\}$, where.

$B_1 = 4\varepsilon\{\lambda T_t[K_t^{2} - 2\varepsilon D_t K_t - (\varepsilon^2-\varepsilon-1)(\varepsilon^2+\varepsilon-1)D_t^{2}] + 36\delta\varepsilon\beta\phi_t^{2}(1+\varepsilon)\frac{^2\}}{(1+\varepsilon)}{}^2\phi_t^{2}$, and $B_2 = 2\{\lambda T_t[K_t + (\varepsilon^2-\varepsilon-1)D_t]\frac{^2 - 36\delta\varepsilon^2\beta\phi_t^{2}(1+\varepsilon)\}}{(1+\varepsilon)\phi_t^{2}}$,

the improved revenue-sharing contract can coordinate the supply chain.

Proof: When both the retailer and the supplier obtain more profits than under normal temperature, the improved revenue-sharing contract is effective to encourage the supplier to adopt cold-chain transportation.

Let $\prod_{rt}^{2} \geq \prod_{rs}^{*} \geq \prod_{rt}^{*} = \prod_{rt}^{1}$, $\prod_{st}^{2} \geq \prod_{ss}^{*} \geq \prod_{st}^{*} = \prod_{st}^{1}$;

We can get

$$\frac{4\varepsilon\left\{\lambda T_t\left[K_t^{2} - 2\varepsilon D_t K_t - (\varepsilon^2-\varepsilon-1)(\varepsilon^2+\varepsilon-1)D_t^{2}\right] + 36\delta\varepsilon\beta\phi_t^{2}(1+\varepsilon)^2\right\}}{(1+\varepsilon)^2\phi_t^{2}} \geq \frac{3\lambda T_s(K_s - \varepsilon D_s)^2}{\phi_s^{2}},$$

$$\frac{2\left\{\lambda T_t[K_t + (\varepsilon^2-\varepsilon-1)D_t]^2 - 36\delta\varepsilon^2\beta\phi_t^{2}(1+\varepsilon)\right\}}{(1+\varepsilon)\phi_t^{2}} \geq \frac{3\lambda T_s(K_s - \varepsilon D_s)^2}{\phi_s^{2}} \neq.$$

Theorem 5 shows that if the above conditions are met, even if the cold-chain logistics cost exceeds the threshold, the supplier will choose the cold-chain transportation. Compared with normal temperature and cold-chain transportation without a contract, all profits of the supply chain are increased, which proves that a win-win situation between the retailer and the supplier can be achieved and the agri-product supply chain can be coordinated. Consequently, the retailer and the supplier have enough motivation to accept the improved revenue-sharing contract. In addition, the supplier adopts cold-chain transportation for all fresh products, which can reduce value loss, ensure food safety and increase the utility of consumers.

6 Numerical analysis

In the above sections, we theoretically build models under cold-chain transportation and normal temperature transportation, and discuss how to coordinate the supply chain under the cost-sharing contract and the improved revenue-sharing contract. In order to illustrate the theoretical results, we present some numerical examples in this section. Fresh food supermarket B and its supplier A selling Zhanhua winter jujube form a two-echelon supply chain. The parameters are summarized in Table 2.

The freshness of Zhanhua winter jujube reaching the retailer is 0.75 under normal temperature transportation and 0.95

Table 2 The parameters

c_m	η	λ	θ_s	ϕ_s	T_s	c_s	θ_t	ϕ_t	T_t	c_t
0.5	0.8	100	0.75	0.8	7	3	0.95	0.96	30	6

under cold-chain transportation. Obviously, cold-chain transportation can reduce quantity loss and quality loss.

6.1 Optimal decisions under cold-chain transportation and normal temperature transportation

We can capture the effects of customers' sensitivity to price and freshness on equilibrium decisions and profits under cold chain transportation and normal temperature transportation. Figures 2(a) and 2(b) show that the optimal wholesale price and retail price under cold-chain transportation are always higher than those under normal temperature transportation, which is consistent with Theorem 1(1). With the increase of customers' sensitivity to price, the optimal wholesale price and the optimal retail price will decrease. Intuitively, because customers are more sensitive to the freshness of agri-products, the whole supply chain must increase the freshness of the products, resulting in the increase of wholesale price and retail price. Figures 2(c) and 2(d) illustrate that when consumers' sensitivity coefficient to price is in lower range, the retailer and the supplier benefit more from cold-chain transportation than normal temperature transportation. Because consumers are not sensitive to retail price, they pay more attention to non-price factors, such as freshness and service. As a source of high gross profit for supply chain members, such consumers can accept the cost transfer brought by cold chain transportation. Figures 3(c) and 3(d) show that when consumers' sensitivity to freshness of agri-products is sufficiently large, the supplier and the retailer will be better under cold-chain transportation. Otherwise, the supply chain members can obtain higher profits under normal temperature transportation. Additionally, in two transportation modes, increasing consumers' sensitivity to freshness can reduce the profits of the supplier and the retailer first, and then increase the profits, which is very interesting. In fact, when customers become

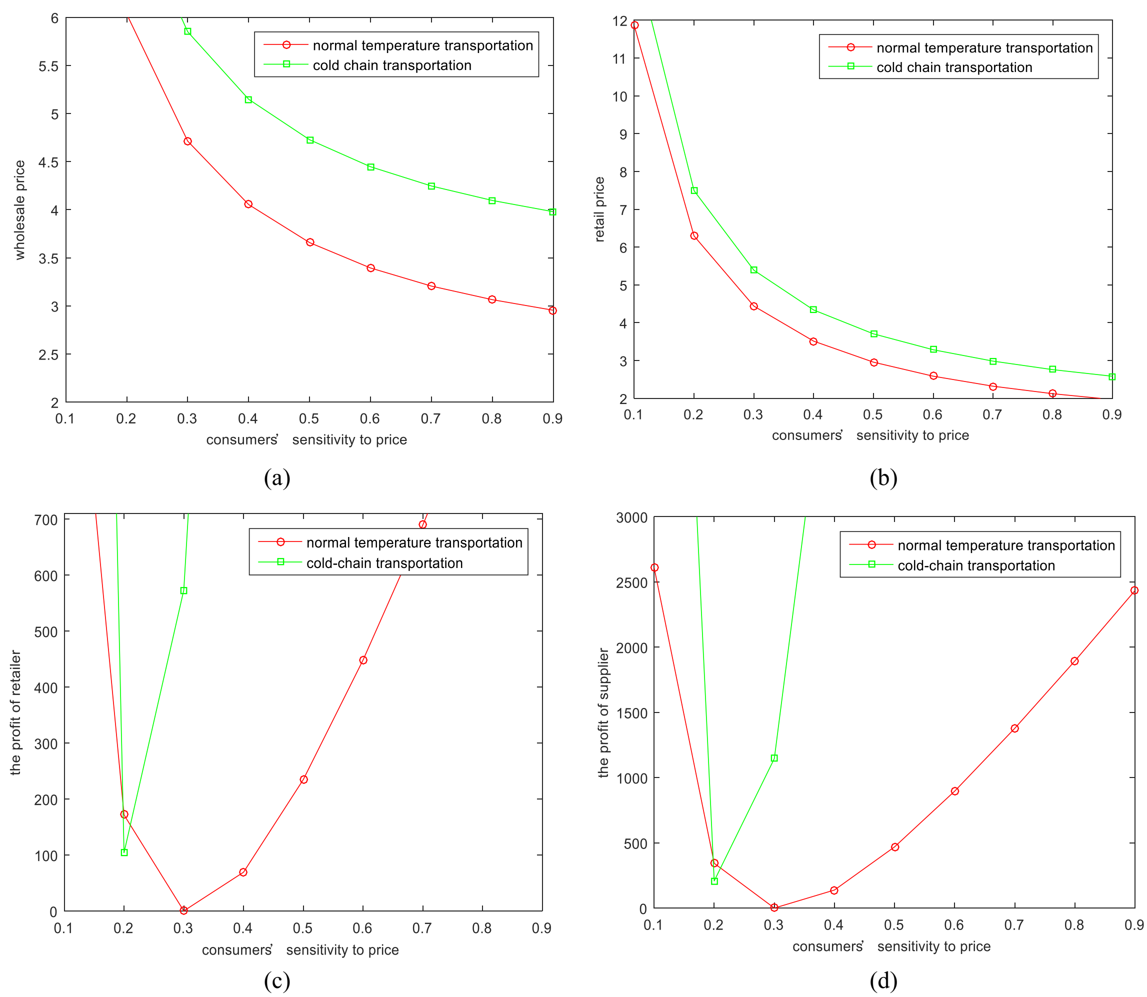


Fig. 2 The effect of consumers' sensitivity to price on optimal decisions in two transportation modes

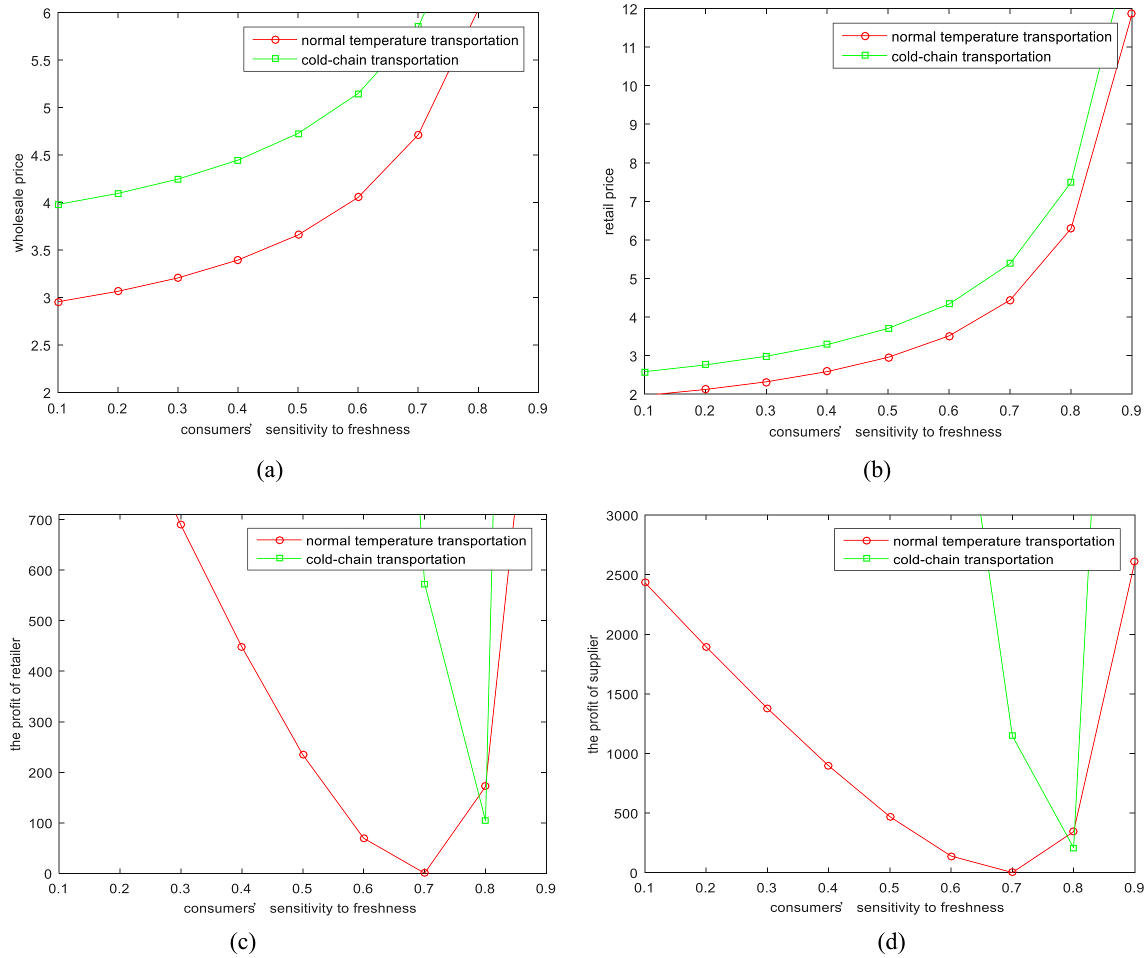
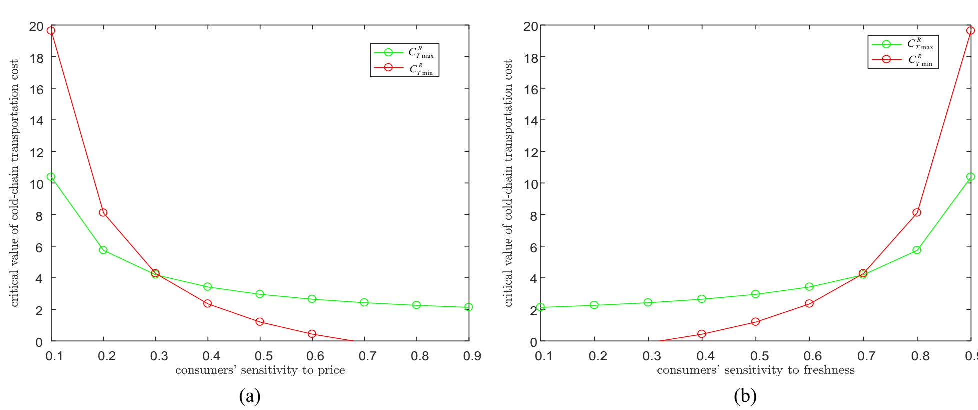


Fig. 3 The effect of consumers' sensitivity to freshness on optimal decisions in two transportation modes

more and more sensitive to freshness, a high level of cold-chain service is essential to offset the high extra cost of value loss and increases market demand. Thus, the profits of the supplier and the retailer are improved.

According to Theorem 2, there is a thresholds value of cold-chain transportation cost. Only when the cold-chain transportation cost is within a certain range, the supplier benefits more from the cold-chain transportation mode; otherwise, the supplier chooses the normal temperature transportation for its own profit. Figures 4(a) and 4(b) show the relationship between the critical value of cold-chain transportation cost and consumers' sensitivity to price and freshness, respectively. It is found that when $\beta \le 0.3$, $\alpha \ge 0.7$, if $C^R_{T\min} \le c_t \le C^R_{T\max}$, the supplier can't get more profits from cold-chain transportation, so the agri-products will be transported at normal temperature. Through the above analysis, it is beneficial for the retailer when the supplier adopts cold-chain transportation mode. It is clear from Fig. 4 that

Fig. 4 The relationship between consumers' sensitivity to price and freshness and critical value of cold-chain transportation cost



critical value of cold-chain transportation cost is affected by consumers' sensitivity to price and freshness. Because the retailer has many years of marketing experience and knows customers very well, it can transfer consumers' information (consumers' sensitivity to price and freshness) to the supplier, so that the supplier can adjust its cold chain transportation cost by re-planning the transportation route. A win-win situation is that under cold-chain transportation, not only the fresh goods are transported, but also the profits of supply chain members are improved.

6.2 The cost-sharing contract

Based on the analysis in Section 6.1, when customers are concerned about the freshness of agri-products, $\alpha = 0.75$, $\beta = 0.25$, we can know that $c_t \in (4.81, 5.81)$ from Fig. 4(b). The supplier will not adopt cold-chain transportation because of higher cost of cold-chain transportation. In the cost-sharing contract, the retailer bears a part of the cold-chain transportation cost. The effectiveness of the cost-sharing contract is verified.

Figure 5 shows that in the cost-sharing contract, the supplier's profit is always lower than that without a coordinated mechanism. According to the theoretical analysis, there are no differences in some equilibrium decisions, such as retail price and the profits of two supply chain members with the cost-sharing contract and without a contract. Therefore, we can learn that the cost-sharing contract can't coordinate the supply chain.

In addition, the wholesale price set by the supplier decreases with the increase of cost-sharing coefficient. For the supplier, a part of the cold-chain transportation cost borne by the retailer is equal to the profit loss caused by the lower wholesale price.

6.3 The improved revenue-sharing contract

$\alpha = 0.75$, $\beta = 0.25$, $c_t = 5 \in (4.81, 5.81)$. After the introduction of improved revenue-sharing contract, the relationship among the retailer's revenue-sharing ratio, the supplier's transfer fee and supply chain members' profits are shown in the following Figs. 6 and 7.

When the retailer's revenue-sharing ratio and the supplier's transfer fee are within a certain range, the profit of the retailer and the supplier is optimal under the improved revenue-sharing contract ($\prod_{rt}^2 \geq \prod_{rs}^* \geq \prod_{rt}^* = \prod_{rt}^1; \prod_{st}^2 \geq \prod_{ss}^* \geq \prod_{st}^* = \prod_{st}^1$). Therefore, when the supplier chooses the cold-chain transportation, supply chain members benefit from it, customers can buy fresher products, the performance of the supply chain has also been improved.

Figure 6 shows that under the coordination condition of $\varepsilon \in (0.41, 1)$ and $\delta \in (50, 100)$, the retailer's profit is always greater than that of normal temperature transportation and it decreases with the decrease of the supplier's transfer fee when the retailer's revenue-sharing ratio remains unchanged. The retailer's profit decreases with the increase of the revenue-sharing ratio.

It can be seen from Fig. 7 that the retailer's revenue-sharing ratio and the supplier's transfer fee have a greater impact on the supplier's profit coordination. After the introduction of a contract under cold chain transportation, when the transfer fee increases, the supplier's profit will decrease. We notice that when the transfer fee remained unchanged and the revenue-sharing ratio is between 0.3 and 0.5, the supplier's profit drops sharply. When the retailer's revenue-sharing ratio is fixed, the supplier's profit decreases slowly with the increase of transfer fee. Compared with the transfer fee, the profit shared by the retailer accounts for a large part of the supplier's profit. In addition, when the retailer's revenue-sharing ratio and transfer fee are within a certain range, the supplier's profit will be higher than that under normal temperature transportation.

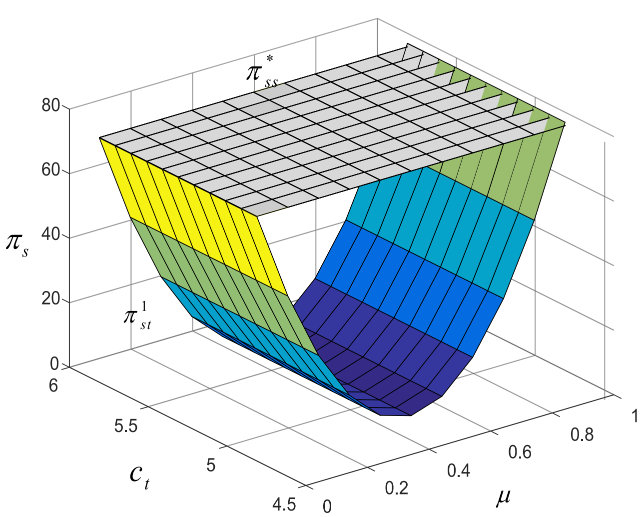


Fig. 5 The relationship among the supplier's profit, cold-chain transportation cost and cost-sharing coefficient

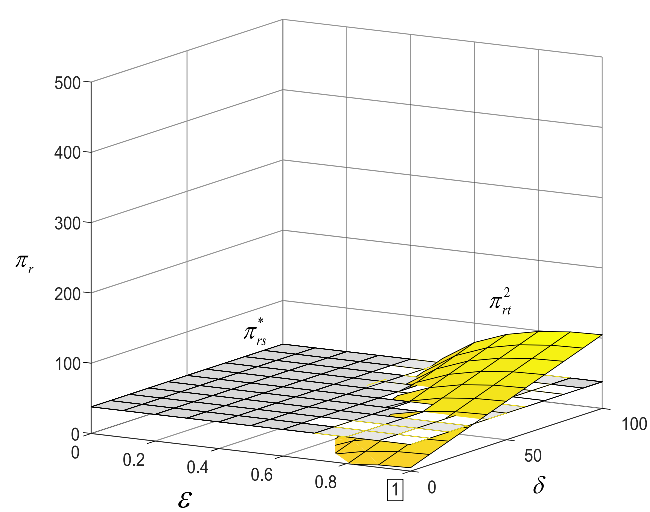


Fig. 6 The relationship among the retailer's profit, transfer fee and revenue-sharing ratio

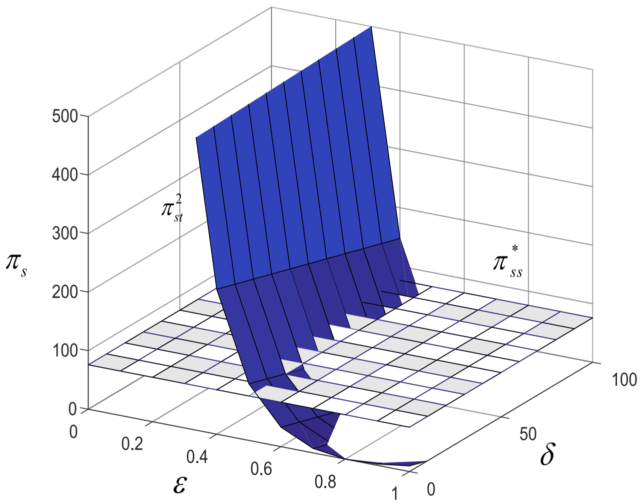


Fig. 7 The relationship among the supplier's profit, transfer fee and revenue-sharing ratio

7 Conclusions

This study explores the impact of transportation modes on the value loss of fresh agri-products. Firstly, the costs and profit under normal temperature transportation mode and cold chain transportation mode are analyzed and compared. Then, according to the critical value of cold-chain logistics cost, the conditions for the supplier to choose different transportation modes are obtained.

In the decentralized decision-making model, there is a critical value of the cold-chain logistics cost C_T^R. According to Numerical Analysis, C_T^R is a function of consumers' sensitivity to price β and consumers' sensitivity to freshness α. When the cold-chain logistics cost is within the critical value range, the supplier will choose cold-chain transportation; otherwise, two coordinated contracts will be introduced to increase profits of both sides. Lastly, we verify the validity of the two contracts. Combined with numerical analysis, the following conclusions can be obtained.

(1) The supplier chooses cold chain transportation to maximize its own interests. The supplier will choose cold chain transportation without coordinating the contract if the transportation cost is within the threshold. In the case of improved revenue-sharing contract, even if the cold-chain transportation cost exceeds the threshold value, as long as the revenue-sharing ratio and transfer fee meet certain conditions, the supplier still chooses cold-chain transportation, and both of them can get the optimal profit.

(2) Under the condition of symmetric information about consumers' sensitivity to freshness, when the cold-chain transportation cost can't be changed in the short term, the improved revenue-sharing contract can achieve Pareto improvement, which requires mutual trust among supply chain members.

The main contributions of this paper are as follows. There is value loss including quality loss and quantity loss in fresh products during the whole process from picking to dining table. In the past, the research on controlling value loss mainly focused on the retailer's freshness-keeping efforts. The supplier's choice of transportation mode is also a method to reduce the value loss, which hasn't been studied yet. This paper discusses the freshness-keeping technology from the perspective of transportation mode, which is more realistic and targeted, and provides operation guidance for small and medium-sized enterprises. Under the condition that the supplier chooses normal temperature transportation, an improved revenue-sharing contract is proposed, which can achieve a win-win situation. In addition, this study contributes to improving the utilization rate of cold-chain logistics and reduce the circulation loss of agri-products. What's more important, it ensures food safety and health.

There are several topics worthy of further research. This paper analyzes the supplier's logistics mode, that is, the quantification of freshness-keeping effort. A natural extension is to study the retailer's freshness-keeping effort and investigate the impact of different transportation modes. Since the arrival rate of consumers at any time is assumed to be constant in this study, another interesting possibility is to test a random situation. Lastly, our model can also be extended into a multi-channel supply chain.

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