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RESEARCH ARTICLE

Two-Stage Decision Model of Fresh Agricultural Products Supply Chain Based on Option Contract

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ABSTRACT In this paper, we study a two-stage fresh agricultural products supply chain consisting of a producer and a retailer. Fresh agricultural products are prone to quality and quantity loss, so the retailer needs to exert freshness-keeping effort to reduce loss. Since the product's freshness and pricing will affect the market demand, we assume that the pricing of fresh agricultural products follows a two-stage decision, and the price is reduced after the freshness decreases. We compare two-stage decision models under three scenarios: centralized, decentralized, and option contracts to explore the impact of freshness-keeping effort on the supply chain and the coordination effect of option contracts on the supply chain. The results show a critical value of freshness-keeping effort under different decision scenarios. The retailer's profit is directly proportional to the freshness-keeping effort when it is less than the critical value. When it exceeds the critical value, retailer profit is inversely proportional to the freshness-keeping effort. Introducing option contracts can increase the total order quantity, reduce the selling price, and increase the supply chain profit. When the freshness-keeping effort satisfies specific conditions, the total profit under the option contract is equal to the total profit under the centralized decision, and perfect supply chain coordination can be achieved. Finally, the theoretical reasoning and conclusions of the model are verified by numerical simulation, and the influence of freshness-keeping effort on supply chain decision-making and coordination effect is analyzed.

INDEX TERMS Fresh agricultural products, supply chain, freshness-keeping effort, option contract, two-stage decision-making, coordination.

I. INTRODUCTION

With the improvement of consumption level, more and more individuals have higher requirements for the quality of fresh agricultural products. The fresh agricultural products market has also been rapid development. Fresh agricultural product has a short shelf life and is prone to spoilage. Compared with other products, fresh agricultural products have the characteristics of short shelf life and easy corruption. People attach great importance to "waste on the tip of the tongue". However, the "First Mile" of fresh agricultural product distribution is often neglected, resulting in alarming losses in the harvest and post-product-ion stages. In recent years, economic losses caused by improper freshness-keeping of agricultural products have occurred many times. According to statistics, the post-production loss rate of grain, potato, fruit, and vegetable in China is 7%∼11%, 15%∼20%, 15%∼20%, and 20%∼25% respectively, which is different from the advanced level in the world, which has brought significant losses to the supply chain, the society, and even the country. Scholars have pointed out that due to inadequate infrastructure and other reasons, China's fresh agricultural products "eat 1/3, throw away 1/3, rot 1/3", with an annual loss of nearly 200 million tons, resulting in a massive waste of production resources and economic losses to farmers [1], [2], [3], [4], [5].

The significant reasons for these phenomena are the low rate of refrigerated transportation in China, the imperfect freshness-keeping facilities, and the weak awareness of freshness-keeping and cooperation among supply chain members, which lead to the low efficiency of supply chain circulation and decision-making deviation. Therefore, how

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to improve the freshness of fresh agricultural products, pay appropriate freshness-keeping efforts, and design effective incentives to achieve supply chain coordination and maximize the interests of all parties is an important issue we must face.

At present, fresh agricultural products' freshness-keeping work needs to be further strengthened, and the fresh agricultural products market has great potential for development. In the rapidly developing fresh agricultural product market environment, consumers are susceptible to prices, and prices are a direct factor affecting consumers' purchase decisions. Since the freshness of fresh agricultural products will gradually decline over time, if the retailer still sells at the previous price after the product declines, it will affect the consumer's desire to buy, resulting in unsalable products. Therefore, retailers should reduce prices after the freshness decline to promote sales.

In this case, the quality and price of fresh agricultural products will affect market demand. We must make fresh-keeping efforts to maintain the freshness of the product, and secondly, according to the specific circumstances of the freshness, in the second stage of sales to reduce prices to promote sales. Fresh agricultural products supply chain management is essential to developing fresh supply chain enterprises and meeting consumers' needs. However, to meet these requirements, it is not enough to rely solely on the efforts of supply chain members. It requires close cooperation between supply chain members to reduce the loss of fresh agricultural products supply chain and improve efficiency. Only by achieving win-win cooperation among supply chain members can we reduce the cost of both parties, attract consumers, and expand the market of fresh agricultural products.

This paper aims to study the coordination problem of the fresh agricultural products supply chain under two-stage decision-making, introduce freshness-keeping effort to depict the quality and quantity loss of fresh agricultural products and introduce option contracts to achieve supply chain coordination. We will address the following research questions:

- In the production and sales process of the fresh agricultural products supply chain, should the two supply chain members, namely producers and retailers, independently decide the order quantity, freshness-keeping effort, and sales price?
- If not, are there different types of new contracts that can coordinate the supply chain?
- Can you increase product freshness and reduce quantity loss through incentives?
- How do market changes (such as freshness-keeping effort, order quantity, and sales price) affect supply chain decisions and profits?
- How are the two new contract policies implemented? The supply chain is easy to coordinate, in which case, the supply chain is not easy to coordinate. In order to answer these questions, we will develop and establish mathematical models of centralized, decentralized, and option contract fresh agricultural products supply chain, respectively.

We will explore and describe the optimal decision-making problems of two supply chain members in three different fresh agricultural product supply chain structures and analyze the impact of freshness-keeping effort on supply chain decisions and profits. We will cite two-stage pricing and option contracts to coordinate this supply chain. These helps improve supply chain performance and contribute to developing the fresh agricultural products market.

The rest of this article is organized as follows. Section II reviews the relevant literature. Section III describes the symbols used in this article and the assumptions of the model. In Sections IV to VI, we design the profit models of retailers and manufacturers under two-stage pricing decisions and study the optimal decision-making problems of retailers and manufacturers under decentralized, centralized, and option contracts, respectively. In section VII, numerical analysis is carried out. Section VIII gives the concluding observations and provides directions for future research. The appendix (A-M) introduces the technical proof of this study from beginning to end.

II. LITERATURE REVIEW

Due to the perishable nature of fresh agricultural products [6], [7], [8], [9], [10], there will be an inevitable loss when the product is transported to the retailer. Therefore, the retailer must pay some freshness-keeping effort to reduce the loss of fresh agricultural products. Losses include quality loss and quantity loss. Quality loss refers to the decline of product freshness, and quantity loss refers to the saleable quantity loss of products. At present, many scholars have considered the loss of fresh agricultural products. Lee et al. [11] designed a deteriorating inventory model with inventory-dependent demand, considering the impact of fresh-keeping technology investment on product freshness, and considered the optimal replenishment strategy for fresh-keeping technology investment while maximizing the total profit per unit time. Yan et al. [12] consider the quality loss of fresh agricultural products, graduate fresh agricultural products supply chain coordination problem from the perspective of consumer strategic behavior.

Zheng et al. [4] and Liu et al. [13] consider the relationship between quantity loss and time, Zheng et al. [4] assume that product quantity loss is an endogenous function of time and consider the optimal decision problem of retailers and suppliers. Liu et al. [13] used the exponential function to describe the relationship between product quantity loss and time. They studied the dynamic freshness-keeping effort model of online retailers and offline producers. Cai et al. [2] considered both quantity loss and quality loss of products and considered the optimal decision problem of retailers and suppliers. Ma et al. [14] considered both quality loss and quantity loss of fresh agricultural products, considered both quantity and quality loss as endogenous variables of fresh-keeping work, and studied the coordination problem of a three-tier supply chain system consisting of a supplier - TPLSP and a retailer. The dynamic decision-making and cost-sharing model of the dual-channel supply chain before and after blockchain application is constructed to maximize profit under specific investment conditions. In the existing research on fresh agricultural products supply chain, most scholars consider freshness-keeping effort from the perspective of quality loss and quantity loss, respectively. Based on the existing research, this paper simultaneously considers the quality loss and quantity loss of fresh agricultural products and studies freshness-keeping effort from the retailers' perspective. It is assumed that retailers take freshness-keeping measures during and after the transportation of products to ensure their freshness of products.

Supply chain coordination can realize the benefit sharing of all parties. How to achieve supply chain coordination is a problem that scholars have been exploring. In recent years, many scholars have used the contract to coordinate the supply chain, and contracts can improve supply chain performance and efficiency [15], [16]. The contract to coordinate the supply chain can achieve good results [17], [18], [19], [20], [21], [22], [23], [24]. Typical supply chain contracts include wholesale contracts [25], quantity flexibility contracts [26], buyback contracts [27], quantity discount contracts [28], sales rebate contracts [29], revenue sharing contracts [30], two-stage pricing contracts [31]and option contracts [32]. These contracts can promote coordination among supply chain members, but in this paper, we mainly use two-stage pricing contracts and option contracts.

Due to the perishable characteristics of fresh agricultural products, the market demand is susceptible to the freshness and price of fresh agricultural products. Retailers' unreasonable pricing strategy will lead to unsold product sales. Therefore, to sell all fresh agricultural products, retailers tend to adopt a staged dynamic pricing strategy and a price reduction strategy in the latter stage of freshness decline to reduce losses. Regarding the dynamic pricing of fresh agricultural products, Feng [33] considered the dynamic optimization model of dynamic pricing and optimal replenishment of quality investment for perishable products with deteriorating quality and quantity and obtained the optimal joint dynamic pricing, quality investment, and replenishment strategy. Yang et al. [34] combined dynamic pricing with information disclosure, considered a model of a monopoly retailer selling fresh agricultural products to customers with different views on product quality over a given period, derived optimal pricing and information strategies to help retailers effectively sell fresh agricultural products and promote sustainable development. Kayikci et al. [35] used real-time Internet of Things (IoT) sensor data as a novel contribution to determine the retailer's pricing in different stages of the sales season. Multi-stage dynamic programming method was used to determine the pricing strategy of bulk agricultural products. The effects of sales price, replenishment amount, discount rate, and freshness fraction on profit and food waste were evaluated, and the optimal pricing strategy was formulated to promote sales and increase profits. Fan et al. [36] studied the dynamic pricing strategy of multi-batch fresh products matching real-time freshness. They proposed four heuristic replenishment strategies based on the freshness of the previous batch of fresh products and the inventory. It is considered that the order quantity depends on the freshness and residual inventory, and the order point and order quantity decrease with the increase of the initial freshness. Yan et al. [37] studied two dynamic pricing strategies, post-price matching (PM) and delayed post-price matching (DPM), to consider consumer behaviors in different types of consumer markets. Li [38] assumed that the demand for perishable products was related to the sales price, reference price, product freshness, and inventory display quantity and studied retailers' inventory and sales price decisions when they were risk-neutral and loss averse.

The freshness of fresh agricultural products will gradually decay over time, so it is inevitable for retailers to adopt price reductions in the second stage of freshness decay. The two-stage pricing decision can solve the problem of product stagnation. In real life, many supermarkets will uphold that fresh products do not stay overnight and discount fresh products at 8:00 p.m., for example, Fresh Hema and Yonghui Supermarket. Therefore, this paper adopts the two-stage pricing strategy in dynamic pricing to study the coordination effect of the fresh agricultural products supply chain, which can effectively reduce social losses and has practical significance.

Many scholars have studied supply chain option, which can achieve good results in supply chain coordination as a financial tool. Cachon [39] argues that option contracts have the dual effect of repurchase contracts and quantity flexibility contracts and that adding options to supply chain contracts can improve supply chain flexibility and promote better cooperation between parties in the supply chain. Zhao et al. [40] investigated the optimal ordering strategy of retailers under bidirectional option contracts. They studied the coordination effect of bidirectional option contracts on the supply chain from the perspective of the whole chain—Liu et al. [41] combined options with advance purchase discount contracts to study supply chain coordination. Chen et al. [42] studied the optimal ordering strategy of risk-averse retailers under option contracts and found that the risk attitudes of supply chain members affect their decision. Wang et al. [43] compared a joint ordering strategy that included option covenants with a single ordering strategy, noting that the joint ordering strategy was better able to cope with price volatility risk. Wan et al. [44] investigated the role of put options in the supply chain of perishable goods in response to inflation-induced price volatility and demand risk. Wang [45], [46] has analyzed the role of call option and put option in supply chain coordination. Based on considering the loss of fresh agricultural products, the paper introduces put option contract to analyze the retailer's optimal decision-making problem and finds that option contracts can reduce demand uncertainty and product loss. The introduction of call options can coordinate the supply chain and improve Pareto. In summary, option contracts can provide a beneficial coordination effect in supply chain coordination. Therefore, combining option contracts and fresh agricultural products supply chain can reduce supply chain risks and better achieve supply chain coordination.

In summary, most scholars in the current research on fresh agricultural products only consider the effect of freshness. Based on the previous work, this paper introduces freshness efforts to consider both the quality loss and the quantity loss of products simultaneously and describes the loss of fresh agricultural products more accurately. Since the freshness of fresh agricultural products decreases over time, and the freshness affects the selling price and market demand, this paper adopts the two-stage pricing decision in dynamic pricing. When the freshness of the product decreases, the price is reduced and sold to reduce the problem of product stagnation. By combining option contracts and a two-stage pricing decision, the joint contract is used to coordinate the fresh agricultural products supply chain, reduce the supply chain risk, achieve the win-win cooperation of supply chain members, and maximize the profits of the supply chain.

From the above literature review, it can be found that the introduction of option contracts to coordinate the supply chain of fresh agricultural products under two-stage decision-making is a relatively less studied field. No one considers these scenarios simultaneously, such as quality loss and quantity loss of fresh agricultural products, two-stage pricing decisions, and option contracts to explore the coordination of the fresh agricultural product supply chain proposed in this paper. Especially considering that freshness, selling prices, and random factors affect the two-stage demand for fresh agricultural products. In addition, although some scholars use contracts to explore the coordination of the fresh agricultural products supply chain, there are still few kinds of literature that study option contracts and two-stage pricing contracts to coordinate the fresh agricultural products supply chain.

Because of the realistic and theoretical background, we conducted the research proposed in this paper. We integrate all the above cases into a new supply chain framework, considering the quality loss and quantity loss of fresh agricultural products, and try to study the supply chain of fresh agricultural products with option contracts under two-stage decision-making for the first time. We will consider for the first time that the demand for the fresh agricultural products supply chain is affected by freshness, two-stage pricing, and random factors. Then, on this basis, we will study the optimal decisions in three different supply chain scenarios: decentralized, centralized, and option contracts to improve the cooperation of members in the supply chain, thereby improving supply chain performance. Our research can expand the perspective of contract coordination of fresh agricultural products supply chain, help fill the research gap and supplement the existing literature. It will help to better understand the optimal decision-making of a specific fresh agricultural product supply chain in different scenarios, the coordination effect of the extensive use of different contract mechanisms on improving supply chain performance, and help decision-makers use scientific management methods to adapt to market changes. Improve the market development of fresh agricultural products in China. Therefore, whether it is realistic background or theoretical background, this will be an interesting topic.

III. NOTATIONS AND ASSUMPTIONS

In the supply chain system composed of a producer and a retailer, the freshness of fresh agricultural products will decline over time due to the perishable characteristics of fresh agricultural products. If the retailer is still selling at the original price, there may be a situation that cannot be sold. Therefore, the retailer can adopt a two-stage pricing strategy and reduce the price in the second stage of the freshness decline of fresh agricultural products to promote the sale of fresh agricultural products. If the retailer orders too much, it needs to reduce the price, and the order quantity is too small to meet the market demand. If the retailer orders less, unable to meet market demand, the need for secondary ordering. In order to make the producer and the retailer share risks, the producer and the retailer sign an option contract that stipulates that the retailer will pay an option fee to the producer before a natural cycle. At the end of the first stage of the selling period, the retailer can decide whether to exercise the option based on market demand. If the agricultural products ordered cannot meet the market demand, the retailer chooses to execute the option and makes a second order. Otherwise, the option will not be executed.

This paper's relevant variables and parameters are shown in the following table.

Fresh agricultural products have a short shelf life and are prone to spoilage. In logistics and sales, they are prone to loss of product quantity. Retailers can reduce product loss through freshness-keeping effort. Retailers pay freshness-keeping effort are τ. Referring to Cai et al. [2], the freshness index ϑ is used to measure the freshness of products, $\vartheta \in [0,1]$. The closer the value is to 1, the fresher the product is. Product survival rate ϕ is used to represent the proportion of quantity available for sale, $\phi \in [0, 1]$, freshness index, and product survival rate are affected by freshness-keeping effort and other random factors. The expression is: $\vartheta(\tau, \varepsilon_1) = \theta(\tau)\varepsilon_1, \vartheta(\tau, \varepsilon_2) = \theta(\tau)\varepsilon_2, \phi(\tau, \gamma_1) = m(\tau)\gamma_1, \phi(\tau, \gamma_2) = m(\tau)\gamma_2$, where ε_1 and ε_2 are random variables that affect the survival rate ϕ of the first and second stage, γ_1 and γ_2 are random variables that affect the freshness index ϑ of the first and second stage products, $\theta(\tau)$ and $m(\tau)$ are strictly increasing functions about freshness-keeping effort τ. The residual value of fresh agricultural products beyond the life cycle equals 0.

Market demand is related to retail price and freshness index ϑ. Market demand is proportional to freshness, and inversely proportional to the retail price. Reference to additive functions widely used [47], [48], [49], [50], [51], [52], assuming that the first stage product demand function is

TABLE 1. Notations.

Symbol	Description
w	The producer's wholesale price (a decision variable)
Q_D	The retailer's order quantity under decentralized decision (a decision variable)
Q_C	The producer's production under centralized decision (a decision variable)
Qoi	The retailer's order quantity of stage i under option contract (a decision variable)
Qo	The retailer's total order quantity under option contract (a decision variable)
p_{Di}	The retailer's selling price of stage i under decentralized decision (a decision variable)
p_{Ci}	The retailer's selling price of stage i under centralized decision (a decision variable)
p_{Oi}	The retailer's selling price of stage i under option contract (a decision variable)
τ	The retailer's freshness-keeping effort (a decision variable)
c	The unit production cost of the producer
$c(\tau)$	The freshness-keeping cost function
ε_i	The random variable affecting the freshness level of stage i, i=1.2
γ_i	The random variables affecting quantity survival rate of stage i, i=1.2
ξ_i	The random variables affecting market demand of stage i, i=1.2
o	The option price in option contract
e	The executive price in option contract
ϑ	The freshness index
ϕ	The product survival rate
D_i	The market demand, i=1.2
$E[\pi_{DRi}]$	The retailer's expected profit function of stage i under decentralized decision, i=1.2
$E[\pi_{ORi}]$	The retailer's expected profit function of stage i under option contract, i=1.2
$E[\pi_{Ci}]$	The expected profit function of stage i under centralized decision, i=1.2
$E[\pi_{DS}]$	The producer's expected profit function under decentralized decision
$E[\pi_{OSi}]$	The producer's expected profit function of stage i under option contract, i=1.2

$D_1 = d(p_1) + \xi_1$, the second stage product demand function is $D_2 = d(p_2)+\xi_2$, where ξ_1, ξ_2 is a random variable affecting market demand. Assume that obeys uniform distribution, where $\xi_1, \xi_2 \in [A,B]$, suppose $d(p_i) = a_i\theta(\tau)\varepsilon_i - b_ip_i$, where b_i is the price elasticity coefficient, a_i is a constant representing the potential market size. Assume that the requirements for the first stage are determined in the second stage.

The range of freshness-keeping effort is $\tau, \tau \in [\tau^L, \tau^U]$, where τ^L and τ^U represent the minimum and maximum freshness-keeping effort, respectively. Retailers' freshness-keeping effort includes investment in fixed assets, such as cold chain facilities and equipment, logistics information systems, etc., and freshness-keeping activities related to unit products, such as packaging, unit storage costs, etc. Taking freshness-keeping measures requires cost, Cai et al. [53] assume that the unit product freshness-keeping effort cost is $c(\tau)$, it a strictly increasing function of freshness-keeping effort τ, and the retailer determines the freshness-keeping effort by balancing the loss and freshness-keeping cost. Assume that the second stage of the product is sold directly. No freshness-keeping effort is required.

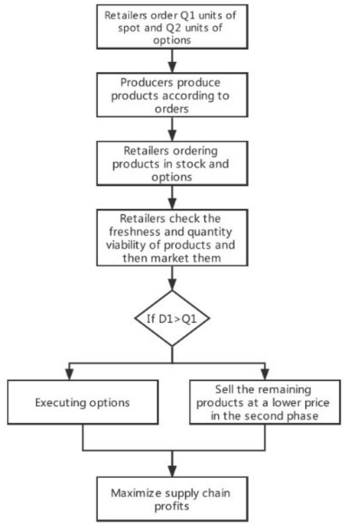

FIGURE 1. Decision flow chart.

Suppose $p > w > c$, to ensure that producers and retailers can profit in production and business activities. Suppose $w > o$, avoid retailers only using wholesale price order spot, incentive retailers order options. Suppose $p > o + e > w$, ensure that retailers can profit through the option contract.

IV. DECENTRALIZED DECISION MODEL

A. RETAILER'S DECISION MODEL

In the traditional order mode, the producer decides the wholesale price w of fresh agricultural products, and the retailer decides the quantity Q_D to order. When the product reaches the target market, the retailer sets the sales price p according to the product's freshness and quantity survival rate.

In a natural period, When the first stage of the market demand $D_1 > Q_Dm(\tau)\gamma_1$, there is $Q_Dm(\tau)\gamma_1 - d(p_1) < \xi_1 \leq B$, retailers order less than the number of products in the first stage of market demand, the order quantity cannot meet all the needs of customers in the market; when the market demand $D_1 \leq Q_Dm(\tau)\gamma_1$, there is $A \leq \xi_1 \leq Q_Dm(\tau)\gamma_1 - d(p_1)$, the retailer orders more than the first phase of the market demand of the product quantity, will cause some fresh agricultural products cannot be sold, the retailer will take the second phase of the price reduction way to deal with the remaining products.

The expected profit function of a retailer in the first stage is

$$E[\pi_{DR_1}] = p_{D1}E\min(D_1, Q_Dm(\tau)\gamma_1) - (w + c(\tau))Q_D \tag{1}$$

The first is the retailer's first-stage sales revenue, and the second is the retailer's freshness-keeping effort cost and wholesale cost.

When the number of products ordered is more than the demand in the first stage, some products will be reduced in price and continue to be sold in the second stage. When the second phase of the market demand $D_2 > (Q_D m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$, there is $Q_D m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2) < \xi_2 < B$, the first phase is when the remaining products can be sold. When the second phase of the market demand $D_2 < (Q_D m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$, there is $A < \xi_2 < Q_D m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2)$, there will be some products that cannot be sold.

The expected profit function of a retailer in the second stage is

$$E\left[\pi_{DR_2}\right] = p_{D2}E\min[D_2, (Q_D m(\tau)\gamma_1 - D_1)^+ m(\tau)\gamma_2] \tag{2}$$

The first is the retailer's second-stage sales revenue.

*Proposition*1: Under the decentralized decision, the retailer's optimal order quantity is:

$$Q_D^* = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{D1}}{m(\tau)\gamma_1} - \frac{(w + c(\tau))(B - A)}{p_{D1}m^2(\tau)\gamma_1^2} \tag{3}$$

The optimal pricing for the first stage is as (4), shown at the bottom of the page.

Which $K_{D1} = Q_D m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1$

$$K_{D2} = Q_D m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 + b_1 p_{D1} m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2$$

The optimal pricing for the second stage is

$$p_{D2}^* = \frac{4b_2B - 4b_2K_{D2}}{6b_2^2} + \frac{\sqrt{(4b_2B - 4b_2K_{D2})^2 + 12b_2^2(2BK_{D2} - K_{D2}^2 - A^2)}}{6b_2^2} \tag{5}$$

Proof of Proposition 1 is provided in Appendix A.

Corollary 1: For retailers, the freshness-keeping effort should be within a specific range. For any $w > 0$, under the decentralized decision-making, the optimal freshness-keeping effort of retailers is:

When $\tau_D^0 \geq \tau^U$, $\tau^* = \tau^U$

when $\tau^L < \tau_D^0 < \tau^U$, if $0 < w < c(\tau^U)$, so $\tau^* = c^{-1}(w)$, if $w > c(\tau^U)$, so $\tau^* = \tau^U$

when $\tau_D^0 \leq \tau^L$, if $w < c(\tau^L)$, so $\tau^* = \tau^L$, if $c(\tau^L) < w < c(\tau^U)$, so $\tau^* = c^{-1}(w)$

if $w > c(\tau^U)$, so $\tau^* = \tau^U$.

When $\frac{\partial E[\pi_{DR}]}{\partial \tau} = 0$, $\tau = \tau_D^0$, the freshness-keeping effort is at a critical value. When $\tau < \tau_D^0$, the retailer's profit increases with the increase of freshness-keeping effort. When $\tau > \tau_D^0$, the retailer's profit decreases with the increase of freshness-keeping effort, the effect of freshness-keeping effort is marginally decreasing. Suppose when $c(\tau) = w$ the freshness-keeping effort currently is $\tau = c^{-1}(w)$.

Proof of Corollary 1 is provided in Appendix B.

Proposition 1 and Corollary 1 show that in the case of decentralized decision-making, retailers make optimal decisions based on the principle of maximizing their profits. Retailers maximize their interests by determining the optimal order quantity, two-stage optimal pricing, and optimal freshness-keeping effort. The retailer's optimal order quantity and pricing are related to freshness-keeping effort. The freshness-keeping effort of retailers is more significant. It should be controlled in a specific range. Because of the perishable nature of fresh agricultural products, even paying more freshness-keeping effort cannot guarantee that the products are intact. Too much freshness-keeping effort can improve the freshness of fresh agricultural products and cause high fresh-keeping costs. Therefore, the retailer's freshness-keeping effort should be within a specific range.

B. PRODUCER'S DECISION MODEL

Retailers order unit Q_D^* fresh agricultural products to the producer, where the producer's expected profit function is

$$E[\pi_{DS}] = (w - c)Q_D^* \tag{6}$$

Putting (3) into

$$E[\pi_{DS}] = (w - c)\left[\frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{D1}}{m(\tau)\gamma_1} - \frac{(w + c(\tau))(B - A)}{p_{D1}m^2(\tau)\gamma_1^2}\right]$$

The derivative for w,

$$\frac{\partial[\pi_{DS}]}{\partial w_D} = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{D1}}{m(\tau)\gamma_1} - \frac{(2w + c(\tau) - c)(B - A)}{p_{D1}m^2(\tau)\gamma_1^2}\ \frac{\partial^2[\pi_{DS}]}{\partial w_D^2} = -\frac{2(B - A)}{p_{D1}m^2(\tau)\gamma_1^2} < 0,$$

There is a maximum value.

When $\frac{\partial[\pi_{DS}]}{\partial w_D} = 0$,

$$w_D^* = \frac{(B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{D1})p_{D1}m(\tau)\gamma_1}{2(B - A)} - \frac{c(\tau) - c}{2} \tag{7}$$

In the case of decentralized decision-making, producers make optimal decisions based on maximizing their profits and ensuring the maximization of their interests by determining the optimal wholesale price.

$$p_{D1}^* = \frac{4b_1B - 4b_1K_{D1} + \sqrt{(4b_1B - 4b_1K_{D1})^2 + 12b_1^2(2BK_{D1} - K_{D1}^2 - A^2)}}{6b_1^2} \tag{4}$$

V. CENTRALIZED DECISION MODEL

In the case of centralized decision-making, the producer and retailer jointly determine the number of products to be produced Q_C, when the product reaches the target market, the retailer sets the sales price p according to the product survival rate.

In a natural period, when the market demand $D_1 > Q_C m(\tau)\gamma_1$, there is $Q_C m(\tau)\gamma_1 - d(p_1) < \xi_1 \leq B$, at this time, the production quantity in the supply chain is less than the first stage of market demand, then it is not possible to meet the total demand of customers in the market; when the market demand $D_1 \leq Q_C m(\tau)\gamma_1$, there is $A \leq \xi_1 \leq Q_C m(\tau)\gamma_1 - d(p_1)$, at this point in the supply chain, the production quantity is more than the market demand in the first stage, which will result in some fresh agricultural products being unable to be sold. The retailer will take a price reduction for the remaining products in the second stage.

The expected profit function for the first stage of the whole supply chain system is:

$$E[\pi_{C1}] = p_{C1} E \min(D_1, Q_C m(\tau)\gamma_1) - (c + c(\tau))Q_C \tag{8}$$

The first item is the revenue from sales in the first phase of the supply chain system, and the second item is the cost of freshness-keeping effort and wholesale costs.

When there is more production in the supply chain than demand in the first stage, some products will take a price reduction and continue selling in the second stage. When the market demand in the second stage $D_2 > (Q_C m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$, there is $Q_C m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2) < \xi_2 < B$, then the remaining products in the first stage can be sold, when the market demand in the second stage $D_2 < (Q_C m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$, there is, $A < \xi_2 < Q_C m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2)$ then there will be some products cannot be sold.

The expected profit function for the second stage of the whole supply chain system is

$$E\left[\pi_{C_2}\right] = p_{C2} E \min[D_2, (Q_C m(\tau)\gamma_1 - D_1)^+ m(\tau)\gamma_2] \tag{9}$$

The first of these items is the second stage of sales revenue.

Proposition 2: Under centralized decision-making, the optimal production quantity for the entire supply chain is

$$Q_C^* = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{C1}}{m(\tau)\gamma_1} - \frac{(c + c(\tau))(B - A)}{p_{C1} m^2(\tau)\gamma_1^2} \tag{10}$$

The optimal pricing for the first stage is

$$p_{C1}^* = \frac{4b_1 B - 4b_1 K_{C1}}{6b_1^2} + \frac{\sqrt{(4b_1 B - 4b_1 K_{C1})^2 + 12b_1^2(2BK_{C1} - K_{C1}^2 - A^2)}}{6b_1^2} \tag{11}$$

which $K_{C1} = Q_C m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1$, $Z_{C1} = Q_C m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1 + b_1 p_{C1}$

The optimal pricing for the second stage is

$$p_{C2}^* = \frac{4b_2 B - 4b_2 K_{C2}}{6b_2^2} + \frac{\sqrt{(4b_2 B - 4b_2 K_{C2})^2 + 12b_2^2(2BK_{C2} - K_{C2}^2 - A^2)}}{6b_2^2} \tag{12}$$

which

$$\begin{aligned} K_{C2} &= Q_C m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1 p_{C1} m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2 \\ Z_{C2} &= Q_C m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1 p_{C1} m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2 + b_2 p_{C2} \end{aligned}$$

The proof is the same as above for APPENDIX A.

Corollary 2: The freshness-keeping effort should be within a specific range for the overall supply chain system. For any $c > 0$, under the centralized decision, the optimal freshness-keeping effort is

when $\tau_C^0 \geq \tau^U$, $\tau^* = \tau^U$

when $\tau^L < \tau_C^0 < \tau^U$, if $0 < c < c(\tau^U)$, so $\tau^* = c^{-1}(c)$, if $w > c(\tau^U)$, so $\tau^* = \tau^U$

when $\tau_C^0 \leq \tau^L$,if $w < c(\tau^L)$, so $\tau^* = \tau^L$,if $c(\tau^L) < c < c(\tau^U)$, so $\tau^* = c^{-1}(c)$

if $w > c(\tau^U)$, so $\tau^* = \tau^U$.

When $\frac{\partial E[\pi_C]}{\partial \tau} = 0$, $\tau = \tau_C^0$, the freshness-keeping effort is at a critical value. When $\tau < \tau_C^0$, the freshness-keeping effort increases, the overall profit of the supply chain increases, and when $\tau > \tau_C^0$, as the freshness-keeping effort increases, the overall profit of the supply chain decreases, the effect brought by the freshness-keeping effort marginally decrease. Assume that when $c(\tau) = c$, the freshness-keeping effort, $\tau = c^{-1}(c)$.

The proof is the same as above for APPENDIX B.

Proposition 2 and corollary 2 show that in the centralized decision-making mode, the producer and the retailer make integrated decisions and make the optimal decision based on maximizing the ordinary profit of both parties. The two parties jointly determine the optimal order quantity and the two-stage optimal pricing and optimal freshness-keeping effort to ensure the maximization of the interests of both parties. In this case, the whole supply chain freshness-keeping effort is not the more significant. It should be controlled within a specific range.

Corollary 3: Assume that price p is an exogenous variable and that the retailer's order quantity is less than the optimal production quantity for the entire supply chain in the centralized decision situation, i.e., $Q_C^* > Q_D^*$.

Proof of Corollary 3 is provided in Appendix C.

Corollary 4: Assuming that the order quantity Q is an exogenous variable, the optimal pricing of the retailer is more excellent under a decentralized decision compared to the centralized decision, $p_{D1}^* > p_{C1}^*, p_{D2}^* > p_{C2}^*$.

Proof of Proposition 1 is provided in Appendix D.

Corollaries 3 and 4 show that the retailer's optimal order quantity in the decentralized decision-making model is lower than the optimal production quantity in the centralized decision-making, and the optimal pricing is higher. Compared with decentralized decision-making, centralized decision-making under the retailer and supplier integration, producers tend to produce more products, and retailers tend to sell at lower prices. Although the pricing is reduced, the overall profit of the supply chain is higher due to more sales. Therefore, to promote cooperation between supply chain members and maximize the benefits of supply chain members, it is necessary to introduce contracts to coordinate the supply chain.

VI. OPTION DECISION MODEL

A. RETAILER'S DECISION MODEL

At the beginning of a natural cycle, the retailer first orders Q_{O1} units of spot fresh agricultural products from the producer and purchases an option on Q_{O2} units. The retailer usually considers the need to execute the option in the second stage.

In a natural cycle, when the market demand $D_1 > Q_{O1}m(\tau)\gamma_1$ in the first stage, there is $Q_{O1}m(\tau)\gamma_1 - d(p_1) < \xi_1 \leq B$, at which time the quantity of products ordered by the retailer is less than the market demand in the first stage, it will not be able to meet the total demand of customers in the market. The retailer will consider executing options in the second stage; when the market demands $D_1 \leq Q_{O1}m(\tau)\gamma_1$, there is $A \leq \xi_1 \leq Q_{O1}m(\tau)\gamma_1 - d(p_1)$, which the retailer orders more than the number of products in the market demand in the first stage, which will cause some fresh agricultural products to be unsold. The retailer will take a price reduction for the remaining products in the second stage.

The expected profit function for the first stage of the retailer is

$$E[\pi_{OR1}] = p_{O1}E\min(D_1, Q_{O1}m(\tau)\gamma_1) - (w + c(\tau))Q_{O1} - oQ_{O2} \tag{13}$$

The first item is the retailer's sales revenue, the second item is the retailer's cost of freshness-keeping effort and wholesale cost for ordering spots, and the third item is the purchase cost of the option.

When the second stage market demand $D_2 > (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$, there is $Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2) < \xi_2 \leq B$, at which point the retailer will execute the option, and when $D_2 - (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2 < Q_{O2}m(\tau)\gamma_1$, execute $D_2 - (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$ units of the option, and when $D_2 - (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2 \geq Q_{O2}m(\tau)\gamma_1$, execute units of the option. When the second-stage market demand $A < \xi_2 \leq Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2)$, there is $A < \xi_2 \leq Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2)$, no option is executed, and a price reduction is taken in the second stage.

The expected profit function for the second stage of the retailer is

$$\begin{aligned} E[\pi_{OR2}] = {} & p_{O2}E\min[D_2, (Q_{O1}m(\tau)\gamma_1 - D_1)^+ m(\tau)\gamma_2] \\ & + (p_{O1} - e)E\min\{[D_2 - (Q_{O1}m(\tau)\gamma_1 \\ & - D_1)m(\tau)\gamma_2]^+, Q_{O2}m(\tau)\gamma_1\} \end{aligned} \tag{14}$$

The first item represents the sales revenue from the retailer's disposal of the product at a reduced price, and the second item represents the retailer's profit from the execution of the option.

Proposition 3: Under the option contract, the optimal spot order quantity for the retailer is

$$Q_{O1}^* = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1p_{O1}}{m(\tau)\gamma_1} - \frac{(w + c(\tau))(B - A)}{p_{O1}m^2(\tau)\gamma_1^2} \tag{15}$$

The optimal option purchase volume is as (16), shown at the bottom of the page.

The optimal pricing for the first stage is

$$p_{O1}^* = \frac{4b_1B - 4b_1K_{O1}}{6b_1^2} + \frac{\sqrt{(4b_1B - 4b_1K_{O1})^2 + 12b_1^2(2BK_{O1} - K_{O1}^2 - A^2)}}{6b_1^2} \tag{17}$$

Which $K_{O1} = Q_{O1}m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1$

The optimal pricing for the second stage is as (18), shown at the bottom of the next page.

Which

$$\begin{aligned} K_{O2} &= Q_{O1}m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1p_{O1}m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2, \\ K_{O3} &= Q_{O1}m^2(\tau)\gamma_1\gamma_2 + Q_{O2}m(\tau)\gamma_1 \\ &\quad - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 + b_1p_{O1}m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2 \end{aligned}$$

Proof of Proposition 3 is provided in Appendix E.

Corollary 5: For the retailer, the freshness-keeping effort paid should be within a specific range, and for any $w > 0$,under the option contract, the optimal freshness-keeping effort for the retailer is

When $\tau_O^0 \geq \tau^U$, $\tau^* = \tau^U$

when $\tau^L < \tau_O^0 < \tau^U$, if $0 < w < c(\tau^U)$, so $\tau^* = c^{-1}(w)$, if $w > c(\tau^U)$, so $\tau^* = \tau^U$

$$Q_{O2}^* = \frac{B - Q_{O1}m^2(\tau)\gamma_1\gamma_2 + a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 - b_1p_{O1}m(\tau)\gamma_2}{m(\tau)\gamma_1} + \frac{a_2m(\tau)\gamma_2 - b_2p_{O2}}{m(\tau)\gamma_1} \tag{16}$$

when $\tau_O^0 \le \tau^L$, if $w < c(\tau^L)$,so $\tau^* = \tau^L$, if $c(\tau^L) < w < c(\tau^U)$, so $\tau^* = c^{-1}(w)$

when $w > c(\tau^U)$, so $\tau^* = \tau^U$.

When $\frac{\partial E[\pi_{OR}]}{\partial \tau} = 0$, $\tau = \tau_O^0$,the freshness-keeping effort is at a critical value. When $\tau < \tau_O^0$, the retailer's profit increases with the increase of freshness-keeping effort. When $\tau > \tau_O^0$, the retailer's profit decreases with the increase of freshness-keeping effort, that is, the effect of freshness-keeping effort is marginally decreasing. Suppose when $c(\tau) = w$, the freshness-keeping effort currently is $\tau^* = c^{-1}(w)$.

Proof of Corollary 5 is the same as above for APPENDIX B.

Proposition 3 and Corollary 5 show that after introducing the option contract, the retailer still makes the optimal decision based on maximizing its profit. The retailer maximizes its profit by determining the optimal order quantity, pricing, optimal option purchase quantity, and freshness-keeping effort. Retailers buy a specific number of options, and then decide whether to execute the options according to the market demand. To a specific extent, the retailer's overstock risk is transferred to the manufacturer. The marginal effect of the retailer's excessive freshness-keeping effort is decreasing. Therefore, the freshness-keeping effort must be kept within a specific range, at least not higher than the wholesale price cost.

Corollary 6: Assuming price p is an exogenous variable, the sum of the retailer's spot orders and option purchases is more than the optimal production for the entire supply chain in the centralized decision scenario, i.e., $Q_O^* > Q_C^*$,option contracts can help retailers reduce the risk of overstocking.

Proof of Corollary 6 is provided in Appendix F.

Corollary 7: Assuming Q is an exogenous variable, the retailer's optimal pricing under the option contract is less than the decentralized decision and more than the centralized decision.

$$p_{\mathrm{D1}}^* > p_{\mathrm{O1}}^* > p_{\mathrm{C1}}^*, p_{\mathrm{D2}}^* > p_{\mathrm{O2}}^* > p_{\mathrm{C2}}^*.$$

Proof of Corollary 7 is provided in Appendix G.

Corollary 6 and 7 show that the total order quantity of the retailer is higher than that of the centralized decision after the introduction of the option, and the optimal pricing is between the decentralized and centralized decisions. It shows that purchasing a specific number of options can help the retailer reduce the risk of storing fresh agricultural products. This encourages the retailer to order more products and sell at a lower price, thus expanding sales and maximizing supply chain profits.

B. PRODUCER'S DECISION MODEL

The producer produces $Q_{O1} + Q_{O2}$ units of fresh agricultural products. The retailer orders Q_{O1} units of spot fresh agricultural products from the producer and orders Q_{O2} units of options, then the producer's first stage expected profit function is:

$$E[\pi_{OS1}] = wQ_{O1} - c(Q_{O2} + Q_{O1}) + oQ_{O2} \tag{19}$$

The first term is the producer's revenue from spot sales, the second is the producer's total production costs, and the third is the revenue from the sale of options.

When the second stage market demand $D_2 > (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$, there is $Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2) < \xi_2 \le B$, at which point the retailer will execute the option, and when $D_2 - (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2 < Q_{O2}m(\tau)\gamma_1$, execute $D_2 - (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2$ units of the option, and when $D_2 - (Q_{O1}m(\tau)\gamma_1 - d(p_1))m(\tau)\gamma_2 \ge Q_{O2}m(\tau)\gamma_1$, execute $Q_{O2}m(\tau)\gamma_1$ units of the option. When the second-stage market demand $A < \xi_2 \le Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2)$, there is $A < \xi_2 \le Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2)$, no option is executed.

Therefore, the producer's second-stage expected profit function is:

$$E[\pi_{OS2}] = eE\min\{[D_2 - (Q_{O1}m(\tau)\gamma_1 - D_1)m(\tau)\gamma_2]^+, Q_{O2}m(\tau)\gamma_1\} \tag{20}$$

The first item represents the revenue received by the producer when the retailer executes the option.

Derivation of w,

$$\begin{aligned}\frac{\partial[\pi_{OS}]}{\partial w_O} &= \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1p_{D1}}{m(\tau)\gamma_1} \\ &\quad - \frac{(2w + c(\tau) - c)(B - A)}{p_{O1}m^2(\tau)\gamma_1^2}\frac{\partial^2[\pi_{DS}]}{\partial w_O^2} \\ &= -\frac{2(B-A)}{p_{O1}m^2(\tau)\gamma_1^2} < 0\end{aligned}$$

There is a maximum value. When $\frac{\partial[\pi_{OS}]}{\partial w_O} = 0$,

$$w_O^* = \frac{(B + a_1\theta(\tau)\varepsilon_1 - b_1p_{O1})p_{O1}m(\tau)\gamma_1}{2(B-A)} - \frac{c(\tau) - c}{2} \tag{21}$$

Proposition 4: The producer's wholesale price is more significant under the option contract than the decentralized decision, i.e., $w_O^* > w_D^*$.

Proof of Proposition 4 is provided in Appendix H.

$$\begin{aligned}p_{O2}^* &= \frac{4b_2B - 4b_2K_{O2} - 2b_2^2(p_{O1} - e)}{6b_2^2} \\ &\quad + \frac{\sqrt{[4b_2B - 4b_2K_{O2} - 2b_2^2(p_{O1} - e)]^2 + 12b_2^2[2BK_{O2} - K_{O2}^2 - A^2 + 2b_2(p_{O1} - e)(B - K_{O3})]}}{6b_2^2}\end{aligned} \tag{18}$$

Proposition 4 shows that compared with decentralized decision-making, the introduction of option contracts can allow manufacturers to increase the wholesale price. Furthermore, manufacturers do not need to worry about retailers reducing the number of orders due to the high wholesale price, which illustrates the coordination effect of option contracts.

Corollary 8: When the wholesale price is determined, when $\tau^L < \tau^0 < \tau^U$, and $0 < w < c(\tau^U)$, there is $\tau_O^* > \tau_D^*$, when $\tau_O^0 \le \tau^L$, and $c(\tau^L) < w < c(\tau^U)$, there is $\tau_O^* > \tau_D^*$.

Proof of Corollary 8 is provided in Appendix I.

Corollary 8 shows that when the manufacturer's wholesale price is determined, the optimal solution of the freshness-keeping effort is also determined. When the freshness-keeping effort under the option contract is higher than the decentralized decision, indicating that the option contract can motivate the retailer to pay more freshness-keeping effort.

C. THE COORDINATION EFFECT OF OPTION CONTRACT

The expected profit function of a retailer under an option contract is

$$E[\pi_{OR}] = E[\pi_{OR1}] + E[\pi_{OR2}]$$
$$E[\pi_{OR}] = p_{O1}\frac{2Z_{O1}B - Z_{O1}^2 - A^2}{2(B-A)} - (w + c(\tau))Q_{O1} - oQ_{O2} + p_{O2}\frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} + (p_{O1} - e)\frac{2Z_{O3}B - Z_{O3}^2 - A^2}{2(B-A)}$$

The expected profit function of manufacturers is $E[\pi_{OS}] = E[\pi_{OS1}] + E[\pi_{OS2}]$

$$E[\pi_{OS}] = wQ_{O1} - c(Q_{O2} + Q_{O1}) + oQ_{O2} + e\frac{2Z_{O3}B - Z_{O3}^2 - A^2}{2(B-A)}$$

Therefore, the total profit of the entire supply chain under the option contract is

$$E[\pi_O] = E[\pi_{OS}] + [\pi_{OR}] = p_{O1}\frac{2Z_{O1}B - Z_{O1}^2 - A^2}{2(B-A)} + p_{O2}\frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} + p_{O1}\frac{2Z_{O3}B - Z_{O3}^2 - A^2}{2(B-A)} - c(\tau)Q_{O1} - c(Q_{O2} + Q_{O1})$$

Corollary 9: The profit sharing between retailers and producers can be achieved by adjusting the option price o and the execution price, e. When o, e increases, the retailer's profit decreases, and the producer's profit increases. When o, e decreases, the retailer's profit increases, the producer's profit decreases, and the total profit of the supply chain remains the same.

Proof of Corollary 9 is provided in Appendix J.

1) COMPARISON OF OPTIONS CONTRACTS AND DECENTRALIZED DECISION MAKING

Comparing the total profit of the supply chain under the option contract with that under the decentralized decision, we can get Proposition5.

Proposition 5: Assuming that retail price p is an exogenous variable, the call option contract can play a coordinating role by increasing retailer profits, increasing producer profits, and increasing total supply chain profits under the option contract compared to the decentralized decision.

Proof of Proposition 5 is provided in Appendix K.

Proposition 5 that introducing an option contract can increase the retailer's optimal total order quantity, and the retailer's purchase of a specific number of options can transfer part of the retailer's overstock risk to the producer, thus increasing the retailer's profit. The introduction of options contracts can reduce the producer's optimal wholesale price, but due to the increase in the number of orders, the producer's profit increases, and the total profit of the supply chain increases.

2) COMPARISON OF OPTIONS CONTRACTS AND CENTRALIZED DECISION MAKING

Comparing the total profit of the supply chain under the option contract with that under the centralized decision, we can get Proposition 6.

Proposition 6: Assuming that the retail price p is an exogenous variable, the total supply chain profit under option contracts is smaller than the total profit under centralized decision-making. The total profit of the supply chain under an option contract is lower than that under a centralized decision.

Proof of Proposition 6 is provided in Appendix L.

Proposition 7: When pricing p and order quantity Q are exogenous variables, the difference between total profit under the option contract and the centralized decision becomes smaller and smaller as the freshness-keeping effort τ increases. Furthermore, perfect coordination can be achieved when the freshness-keeping effort is satisfying $\tau* = \tau^N$. τ^N is the solution for the freshness-keeping effort when the total profit difference is 0.

Proof of Proposition 7 is provided in Appendix M.

Proposition 6 and Proposition 7 show that under normal circumstances, the total profit of the supply chain under the option contract is lower than that of the centralized decision. Furthermore, when the freshness-keeping effort meets specific conditions, the total profit of the supply chain under the option contract is equal to the total profit of the supply chain under the centralized decision-making, thus realizing the perfect coordination of the supply chain.

VII. NUMERICAL EXAMPLES

A. SENSITIVITY ANALYSIS OF FRESHNESS-KEEPING EFFORT

Assume that a pair of retailers and producers meet the model's conditions, and the demand for fresh agricultural products

TABLE 2. Optimal decisions.

Decentralized decision	Centralized decision	Option contract
$Q_D{}^* = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{D1}}{m(\tau)\gamma_1} - \frac{(w + c(\tau))(B - A)}{p_{D1} m^2(\tau)\gamma_1^2}$	$Q_C{}^* = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{C1}}{m(\tau)\gamma_1} - \frac{(c + c(\tau))(B - A)}{p_{C1} m^2(\tau)\gamma_1^2}$	$Q_{O1}{}^* = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{O1}}{m(\tau)\gamma_1} - \frac{(w + c(\tau))(B - A)}{p_{O1} m^2(\tau)\gamma_1^2}$
/	/	$Q_{O2}{}^* = \frac{B - Q_{O1} m^2(\tau)\gamma_1\gamma_2 + a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2}{m(\tau)\gamma_1} - \frac{b_1 p_{O1} m(\tau)\gamma_2 - a_2 m(\tau)\gamma_2 + b_2 p_{O2}}{m(\tau)\gamma_1}$
$p_{D1}{}^* = \frac{4b_1B - 4b_1K_{D1}}{6b_1^2} + \frac{\sqrt{(4b_1B - 4b_1K_{D1})^2 + 12b_1^2(2BK_{D1} - K_{D1}{}^2 - A^2)}}{6b_1^2}$	$p_{C1}{}^* = \frac{4b_1B - 4b_1K_{C1}}{6b_1^2} + \frac{\sqrt{(4b_1B - 4b_1K_{C1})^2 + 12b_1^2(2BK_{C1} - K_{C1}{}^2 - A^2)}}{6b_1^2}$	$p_{O1}{}^* = \frac{4b_1B - 4b_1K_{O1}}{6b_1^2} + \frac{\sqrt{(4b_1B - 4b_1K_{O1})^2 + 12b_1^2(2BK_{O1} - K_{O1}{}^2 - A^2)}}{6b_1^2}$
$p_{D2}{}^* = \frac{4b_2B - 4b_2K_{D2}}{6b_2^2} + \frac{\sqrt{(4b_2B - 4b_2K_{D2})^2 + 12b_2^2(2BK_{D2} - K_{D2}{}^2 - A^2)}}{6b_2^2}$	$p_{C2}{}^* = \frac{4b_2B - 4b_2K_{C2} +}{6b_2^2} + \frac{\sqrt{(4b_2B - 4b_2K_{C2})^2 + 12b_2^2(2BK_{C2} - K_{C2}{}^2 - A^2)}}{6b_2^2}$	$p_{O2}{}^* = \frac{4b_2B - 4b_2K_{O2} - 2b_2{}^2(p_{O1} - e)}{6b_2^2} + \frac{\sqrt{[4b_2B - 4b_2K_{O2} - 2b_2{}^2(p_{O1} - e)]^2 + 12b_2^2[2BK_{O2} - K_{O2}{}^2 - A^2 + 2b_2(p_{O1} - e)(B - K_{O3})]}}{6b_2^2}$
$w_D^* = \frac{(B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{D1}) p_{D1} m(\tau)\gamma_1}{2(B - A)} - \frac{c(\tau) - c}{2}$	/	$w_O^* = \frac{(B + a_1\theta(\tau)\varepsilon_1 - b_1 p_{O1}) p_{O1} m(\tau)\gamma_1}{2(B - A)} -$

is relatively stable. Retailers generally adopt the ordering strategy of fixed order quantity. Retailers must decide the optimal selling price and the freshness-keeping effort they pay before ordering fresh agricultural products. Producers need to decide the optimal wholesale price. After determining the wholesale price of the product, the retailer's freshness-keeping effort affects its profit. In order to investigate the effect of freshness-keeping effort on retailers' order quantity and supply chain profit, a set of data is designed for simulation, and conclusions are drawn accordingly.

Assume that the random variables in the demand function for fresh agricultural products obey a uniform distribution on [120, 200], A = 120, B = 200, $w = 8$, $c = 6$, $\varepsilon_1 = 0.9$, $\varepsilon_2 = 0.7$, $\theta(\tau) = \tau^{0.7}$, $m(\tau) = \tau^{0.6}$, $c(\tau) = 1.5e^{2^\tau}$, $b_1 = 5$.

The results in Figure 2 show that when the order quantity is exogenous, the retail price in the first stage is positively related to the freshness-keeping effort paid, and the higher the freshness-keeping effort, the higher the retail price in the first stage. When the quality loss and quantity loss of the products are higher, when the freshness-keeping effort paid is low, and some products are spoiled before they reach the target market, and retailers cannot sell them at high prices. As the freshness-keeping effort increases, the retail price of the second stage increases and decreases, indicating that the freshness effort paid affects the retail price of the second stage by influencing the retail price of the first stage. When the freshness effort tends to 1, the freshness cost paid is too significant and the retail price of the second stage decreases. Because consumers have higher requirements for freshness, and market demand is related to the freshness of products. For enterprises, the fresher the products are, the higher the price consumers are willing to pay for them, and the faster the sales of products will be so that enterprises can obtain higher profits.

The results in Figure 3 when the retail price is exogenous, the retailer's order quantity increases and decreases with the increase of freshness-keeping effort. This indicates that compared with no freshness-keeping, paying a specific freshness-keeping effort can significantly increase the retailer's order quantity. However, after the freshness-keeping effort exceeds a specific range, increasing the freshness-keeping effort at this time will increase the corresponding freshness-keeping cost, thus leading to the retailer's order quantity. Therefore, the freshness effort should not be as significant as possible but should be limited to a specific range. After introducing the option contract, the retailers' order quantity is larger than the order quantity under the centralized decision, which indicates that the option contract can coordinate the supply chain in terms of order quantity, and Corollary 6 is verified. For enterprises, freshness-keeping can increase profits and meet consumers' needs for freshness and create a good reputation. Enterprises will order more products. However, at the same time, enterprises will also find that the freshness of fresh agricultural products will gradually decrease with time. Even if more freshness-keeping efforts are made, they will not

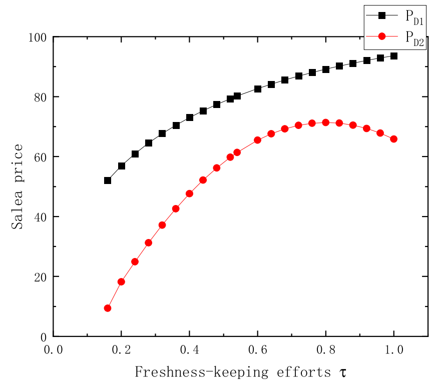

FIGURE 2. **Impact of freshness-keeping effort on retail prices.**

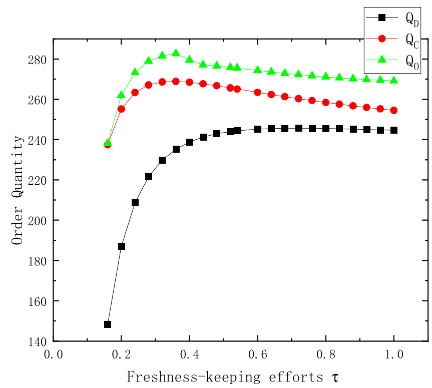

FIGURE 3. **Effect of freshness-keeping effort on order quantity.**

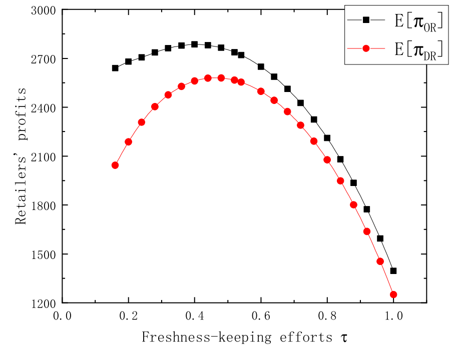

FIGURE 4. **Impact of freshness-keeping effort on retailer profits.**

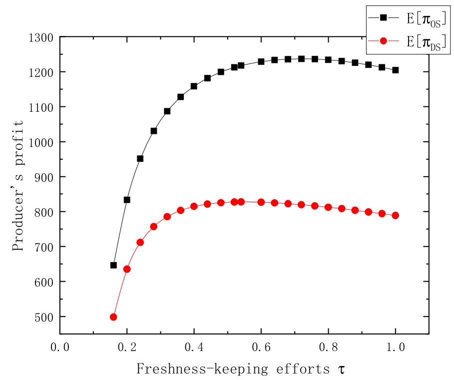

FIGURE 5. **Impact of freshness-keeping effort on producer profits.**

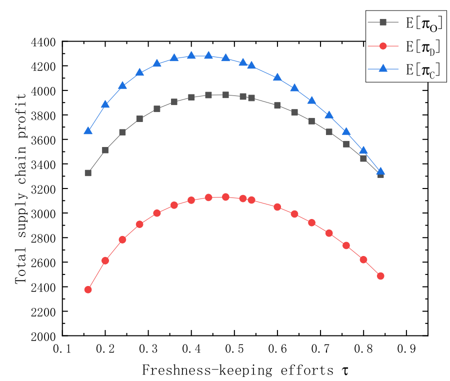

FIGURE 6. **Impact of freshness-keeping effort on total supply chain profits.**

be intact, so freshness-keeping efforts should be controlled within a specific range.

B. IMPACT OF FRESHNESS-KEEPING EFFORT ON PROFITS UNDER OPTION CONTRACTS

Based on the above results, the impact of freshness-keeping effort on retailer and producer profits under option contracts is further discussed. Before the start of a natural cycle, retailers generally adopt a fixed order quantity ordering strategy. After introducing option covenants, retailers can purchase partial quantities of options to hedge their risk. After the producer determines the wholesale price and option price, the retailer decides the spot order quantity and option purchase quantity of the fresh agricultural products and determines the selling price and the freshness-keeping effort to be paid. The freshness-keeping effort affects the profits of all parties in the supply chain. In order to study the effect of freshness-keeping effort on option contracts, a data set was designed for simulation, and conclusions were drawn accordingly. Assuming that at this point $o = 0.5$ and $e = 9$, so that it varies continuously, the effect of freshness-keeping effort on the profits of retailers and producers can be obtained.

The results in Figures 4 and 5 show that under the option contract, both retailer and producer profit increase and decrease with the increase of freshness-keeping effort. Compared with no freshness-keeping effort, the freshness-keeping effort can rapidly increase the profit of retailers and producers. However, when the freshness-keeping effort exceeds a specific range, both retailer profit and producer profit decrease with the increase of freshness-keeping effort, which means that retailers need to pay more freshness-keeping to cost. The increase in cost will lead to a decrease in profit. Therefore, the freshness-keeping effort should be controlled within a specific range, and the increase of freshness-keeping effort beyond this range will lead to a decrease in profit for supply chain members. Since retail enterprises pay the freshness-keeping efforts, freshness-keeping efforts within a specific range can increase profits and meet consumers' needs for freshness. If the fresh-keeping efforts are beyond a specific range, the cost of enterprises is growing, not enough to cover the profits of enterprises, so the profits of enterprises will be less and less. Although the producer does not pay for freshness, the freshness will affect the company's profit by affecting the order quantity. When the freshness exceeds a specific range, the retailer's freshness cost will increase, leading to a decrease in order volume, which affects the producer's profit.

The results in Figure 6 show that the total supply chain profit increases and decreases as the freshness-keeping effort increases. Hence, the freshness-keeping effort is not as significant as possible but should be kept within a specific range. Increasing the freshness-keeping effort beyond this range will lead to a decrease in the supply chain profit. The total supply chain profit under a centralized decision is more significant than that under an option decision. The total profit under the option decision is more significant than that under the decentralized decision, indicating that the option contract can coordinate the supply chain. When the freshness-keeping effort is taken to a specific value, it can achieve perfect coordination.

For the enterprise, as the freshness-keeping intensity increases, the consumer's freshness demand is gradually met. The sales volume of the enterprise will increase, thus increasing the total profit of the supply chain enterprise. However, when the freshness-keeping effort exceeds a certain range, the freshness-keeping cost paid by the enterprise also increases, which in turn affects the sales price and thus the order quantity of the enterprise, thus affecting the profit of retailers and producers, resulting in a reduction of the total profit of the supply chain. Therefore, in production and operation, enterprises should explore the process of the freshness-keeping effort and try to keep the freshness-keeping effort within a reasonable range to achieve maximum profit.

To further demonstrate the robustness of the results, we take the cherries in Yantai, Shandong Province, as an example to analyze the operation process of the cherry-related supply chain. The natural mature cherry in the Yantai area has the characteristics of concentrated mature time, short sales cycle, perishable, expensive price, and high freshness-keeping requirements. In the whole cherry supply chain, after retailers collect cherries from fruit growers, they will take freshness-keeping measures to transport some cherries to all parts of the country by express delivery. However, in this process, the retailer's freshness-keeping efforts are within a specific range. Retailers increase their fresh-keeping efforts, such as increasing ice bags, which will increase the cost of fresh-keeping and freight, and then increase the sales price. Consumers may choose to reduce purchases because the price of large cherries is too high. If the retailer's orders are reduced, it will reduce the purchase of cherries from the producer, so the profits of both the retailer and the manufacturer will be reduced, which is not conducive to maximizing the profits of both parties.

VIII. CONCLUSION

Whether the fresh agricultural products are fresh and the price is reasonable is more and more valued by people. In the production and operation of fresh agricultural products supply chain, should supply chain members invest the more freshness-keeping effort to reduce losses and determine sales prices based on freshness? What is the best decision for supply chain members in this situation? How to design a reasonable incentive mechanism to coordinate the supply chain to maximize profits? All of these are related to the freshness demand of consumers, the interests of supply chain members, and the long-term development of the whole supply chain. This paper investigates the coordination of options contracts in a fresh agricultural products supply chain under two-stage decision-making for a secondary fresh agricultural products supply chain system consisting of a retailer and a producer, considering both quality loss and quantity loss of the product. The main conclusions of this paper are as follows.

1) Under the three decision-making situations of decentralized decision-making, centralized decision-making, and options contract, when the fresh-keeping effort paid by the retailer is less than the critical value, the retailer's profit increases with the increase of the freshness-keeping effort. When the freshness-keeping effort exceeds the critical value because of the perishable attributes of fresh agricultural products, even if more fresh-keeping efforts are paid, the product is not guaranteed to be intact. Too much freshness-keeping effort can improve the freshness of fresh agricultural products and cause high fresh-keeping costs. At this time, increasing the freshness-keeping effort will lead to a decrease in the retailer's profit because of the increase in the fresh-keeping cost. Therefore, the freshness-keeping effort is not the more significant. It should be controlled within a specific range and at least less than the product's wholesale price. The retailer's optimal order quantity and pricing are related to the fresh-keeping effort. Determining the optimal fresh-keeping effort can determine the retailer's optimal order quantity and optimal pricing.

2) We find that compared with the centralized decision, the optimal order quantity and total profit of the decentralized decision are lower, and the optimal selling price of the two stages is higher. Therefore, we conclude that centralized decision-making is always optimal. In addition, introducing an option contract can improve the freshness-keeping effort and maximize the profits of the decentralized supply chain. Options contracts can realize supply chain coordination. For retailers, the total retailer order quantity under the option contract is greater than the producer's production quantity under the centralized decision when the retail price is an exogenous variable. When the order quantity is an exogenous variable, the retail price under both stages of the option contract is less than the retail price under the centralized decision and more significant than the retail price under the decentralized decision. For the producer, the wholesale price under the option contract is higher than that under the decentralized decision.

The introduction of option contracts can increase both the retailer's profit and the producer's profit. Option contracts can promote retailer ordering and thus increase retailer profits. At the same time, it can increase the producer's wholesale price, thus increasing the producer's profit and achieving supply chain coordination. Furthermore, when the freshness-keeping effort is of a particular value, the supply chain system can achieve perfect coordination.

3) The numerical simulation shows that under the three mechanisms of decentralized decision-making, centralized decision-making, and option contract, the order quantity increases with the increase of freshness-keeping effort when the freshness-keeping effort paid by the retailer is less than the critical value. When the freshness-keeping effort exceeds the critical value, the order quantity decreases with increased freshness-keeping effort. Both retailer's and producer's profits under the option contract increase and then decrease with the increase of freshness-keeping effort. Therefore, the freshness effort should be controlled within a specific range, and increasing the freshness effort beyond this range will increase the cost of freshness, which will lead to the reduction of supply chain profit. The total profit of the supply chain under all three mechanisms increases and then decreases with the freshness-keeping effort. The total profit under the option mechanism is between centralized and decentralized decision-making, indicating that the option contract can achieve supply chain coordination. As the strike price and option price increase, the retailer's profit decreases, the producer's profit increases, and the total supply chain profit increases, and the benefit sharing between the retailer and the producer can be achieved by adjusting the strike price and option price between the retailer and the producer.

Our findings convey many interesting management implications. Efficient supply chain management of fresh agricultural products can help supply chain members take risks and maximize profits. For enterprises, how much fresh-keeping efforts and how many products to order are essential issues. Our results can provide a reference for supply chain enterprises in freshness-keeping efforts and various pricing and order quantity decisions to better balance costs and profits. From the perspective of the whole fresh agricultural product supply chain, we combine the two-stage pricing decision and the option contract, which can provide the reference for the supply chain members to introduce financial instruments in the actual operation. Through the reasonable introduction of options, we can make the supply chain of each node enterprise win-win cooperation and make the supply chain more competitive, cooperative, and strategic.

Although this paper provides some findings and management implications, some interesting and challenging topics deserve further study. In this paper, we aim at the unique natural attributes of fresh agricultural products while considering the quality and quantity loss of products. This paper focuses on the coordination role of option contracts from the perspective of two-stage decision-making. However, dynamic pricing of fresh agricultural products also has various forms, and dynamic pricing has the property of decaying over time. Therefore, it is our further research direction to introduce the time factor to portray the dynamic pricing of products and to explore the coordination role of option contracts under the time factor.

APPENDIX A

Proof of Proposition 1. Define inventory factors

$$\begin{aligned} Z_{D2} &= Q_D m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2) \\ &= Q_D m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1 p_{D1} m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2 + b_2 p_{D2} \end{aligned}$$

Rewrite (2) to

$$E\left[\pi_{DR_2}\right] = p_{D2}\left(\int_A^{Z_{D2}} \frac{1}{B-A}dx + \int_{Z_{D2}}^B \frac{Z_{D2}}{B-A}dx\right)$$

$$p_{D2}\frac{2Z_{D2}B - Z_{D2}^2 - A^2}{2(B-A)},$$

$$\frac{\partial E\left[\pi_{DR_2}\right]}{\partial p_{D2}} = \frac{2Z_{D2}B - Z_{D2}^2 - A^2}{2(B-A)} + b_2 p_{D2}\frac{B - Z_{D2}}{B-A}\frac{\partial E\left[\pi_{DR_2}\right]}{\partial p_{D2}} = 0,$$

$$2Z_{D2}B - Z_{D2}^2 - A^2 + 2b_2 p_{D2}B - 2b_2 p_{D2} Z_{D2} = 0$$

let

$$\begin{aligned} K_{D2} &= Q_D m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1 p_{D1} m(\tau)\varepsilon_2 - a_2\theta(\tau)\varepsilon_2 \end{aligned}$$

which $Z_{D2} = K_{D2} + b_2 p_{D2}$

$$\begin{aligned} -3b_2^2 p_{D2}^2 &+ (4b_2 B - 4b_2 K_{D2})p_{D2} \\ &+ 2BK_{D2} - K_{D2}^2 - A^2 = 0 \end{aligned}$$

$$p_{D2}^* = \frac{4b_2 B - 4b_2 K_{D2}}{6b_2^2} + \frac{\sqrt{(4b_2 B - 4b_2 K_{D2})^2 + 12b_2^2(2BK_{D2} - K_{D2}^2 - A^2)}}{6b_2^2}$$

.

Define inventory factor

$$\begin{aligned} Z_{D1} &= Q_D m(\tau)\gamma_1 - d(p_1) \\ &= Q_D m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1 + b_1 p_{D1} \end{aligned}$$

Rewrite (1) to $E\left[\pi_{DR_1}\right] = p_{D1}(\int_A^{Z_{D1}} \frac{1}{B-A}dx + \int_{Z_{D1}}^B \frac{Z_{D1}}{B-A}dx) - (w+c(\tau))Q_D$, Derivation for Q_D and p_{D1} respectively, we can get

$$\frac{\partial E\left[\pi_{DR_1}\right]}{\partial Q_D} = p_{D1} m(\tau)\gamma_1 \frac{B - Z_{D1}}{B-A} - (w + c(\tau)),$$

$$\frac{\partial E\left[\pi_{DR_1}\right]}{\partial p_{D1}} = \frac{2Z_{D1}B - Z_{D1}^2 - A^2}{2(B-A)} + b_1 p_{D1}\frac{B - Z_{D1}}{B-A}$$

$$\begin{vmatrix} \frac{\partial^2 E\left[\pi_{DR_1}\right]}{\partial Q_D^2} & \frac{\partial^2 E\left[\pi_{DR_1}\right]}{\partial Q_D \partial p_{D1}} \\ \frac{\partial^2 E\left[\pi_{DR_1}\right]}{\partial p_{D1}\partial Q_D} & \frac{\partial^2 E\left[\pi_{DR_2}\right]}{\partial p_{D1}^2} \end{vmatrix}$$

$$= \begin{vmatrix} \frac{-p_{D1}m^2(\tau)\gamma_1^2}{B-A} & m(\tau)\gamma_1\frac{B-Z_{D1}-b_1p_{D1}}{B-A} \\ m(\tau)\gamma_1\frac{B-Z_{D1}-b_1p_{D1}}{B-A} & b_1\frac{B-Z_{D1}-b_1p_{D1}}{B-A} \end{vmatrix} < 0$$

is negative, $E[\pi_{DR1}]$ has a maximum point, that is, there are optimal order quantity Q_D^* and optimal pricing p_{D1}^*,Assuming that the first derivative is 0, there is

$$Q_D^* = \frac{B+a_1\theta(\tau)\varepsilon_1 - b_1p_{D1}}{m(\tau)\gamma_1} - \frac{(w+c(\tau))(B-A)}{p_{D1}m^2(\tau)\gamma_1^2}$$

$$p_{D1}^* = \frac{4b_1B-4b_1K_{D1}}{6b_1^2} + \frac{\sqrt{(4b_1B-4b_1K_{D1})^2+12b_1^2(2BK_{D1}-K_{D1}^2-A^2)}}{6b_1^2}$$

APPENDIX B

Proof of Corollary 1. The solution of freshness-keeping effort is $\tau = \tau_D^0$. Because $\tau \in [\tau^L, \tau^U]$, when $\tau_D^0 \geq \tau^U$.At this point, the retailer's critical value of freshness-keeping effort is beyond the maximum range of freshness-keeping effort. Freshness-keeping effort can only take the maximum range, $\tau^* = \tau^U$.

When $\tau^L < \tau_D^0 < \tau^U$, retailers need to associate freshness-keeping effort with freshness-keeping costs, and compare freshness-keeping costs with wholesale prices. Based on freshness-keeping effort costs less than wholesale prices, retailers try to pay more freshness-keeping effort to ensure the freshness of products. If $0 < w < c(\tau^U)$, the retailer pays at most the freshness-keeping effort cost equal to the wholesale price, then $\tau^* = c^{-1}(w)$, if $w > c(\tau^U)$, the retailer can pay as much freshness-keeping effort as possible, then $\tau^* = \tau^U$.

When $\tau_D^0 \leq \tau^L$, the retailer's freshness-keeping effort critical value is lower than the minimum freshness-keeping effort in the freshness-keeping range, if the wholesale price is less than the minimum freshness-keeping effort cost, that is, $w < c(\tau^L)$, then the retailer pays the minimum freshness-keeping effort, there is $\tau^* = \tau^L$; if the wholesale price is between the minimum freshness-keeping effort cost and the maximum freshness-keeping effort cost, that is, $c(\tau^L) < w < c(\tau^U)$, then the retailer pays at most the freshness-keeping cost equal to the wholesale price, there is $\tau^* = c^{-1}(w)$; if $w > c(\tau^U)$, the retailer's wholesale price is greater than the maximum freshness-keeping effort cost, then it can pay as much freshness-keeping effort as possible, at this time, $\tau^* = \tau^U$.

APPENDIX C

Proof of Corollary 3. $Q_C^* - Q_D^* = \frac{(w-c)(B-A)}{pm^2(\tau)\gamma_1^2} > 0$,

APPENDIX D

Proof of Corollary4.

Because

$$p_{D1}^* = \frac{4b_1B-4b_1K_{D1}}{6b_1^2} + \frac{\sqrt{(4b_1B-4b_1K_{D1})^2+12b_1^2(2BK_{D1}-K_{D1}^2-A^2)}}{6b_1^2}$$

As K_{D1} increases, $4b_1B-4b_1K_{D1}$ decreases, so that $M = (4b_1B-4b_1K_{D1})^2+12b_1^2(2BK_{D1}-K_{D1}^2-A^2)$, Derivative of K_{D1} $\frac{\partial M}{\partial K_{D1}} = 8b_1^2(K_{D1}x - B)$, when $K_{D1} < B$, $\frac{\partial M}{\partial K_{D1}} < 0$, M monotonically decreasing. Because $K_{D1} < K_{C1}$,then $> p_{D1}^* > p_{C1}^*$.

Similarly, we can obtain $K_{D2} < K_{C2}$, then $p_{D2}^* > p_{C2}^*$.

APPENDIX E

Proof of proposition 3. Define inventory factor

$$\begin{aligned} Z_{O1} &= Q_{O1}m(\tau)\gamma_1 - d(p_1) \\ &= Q_{O1}m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1 + b_1p_{O1} \\ Z_{O2} &= Q_{O1}m^2(\tau)\gamma_1\gamma_2 - d(p_1)m(\tau)\gamma_2 - d(p_2) \\ &= Q_{O1}m^2(\tau)\gamma_1\gamma_2 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1p_{O1}m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2 + b_2p_{O2} \\ Z_{O3} &= Q_{O1}m^2(\tau)\gamma_1\gamma_2 + Q_{O2}m(\tau)\gamma_1 \\ &\quad - d(p_1)m(\tau)\gamma_2 - d(p_2) \\ &= Q_{O1}m^2(\tau)\gamma_1\gamma_2 + Q_{O2}m(\tau)\gamma_1 - a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 \\ &\quad + b_1p_{O1}m(\tau)\gamma_2 - a_2\theta(\tau)\varepsilon_2 + b_2p_{O2} \end{aligned}$$

Can be rewritten to

$$\begin{aligned} &E[\pi_{OR2}] \\ &= p_{O2}\frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} \\ &\quad + (p_{O1}-e)\frac{2Z_{O3}B - Z_{O3}^2 - A^2}{2(B-A)} \\ &\frac{\partial E[\pi_{OR_2}]}{\partial Q_{O2}} \\ &= (p_{O1}-e)m(\tau)\gamma_1\frac{B-Z_{O3}}{B-A}, \\ &\frac{\partial E[\pi_{OR_2}]}{\partial p_{O2}} \\ &= \frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} \\ &\quad + b_2p_{O2}\frac{B-Z_{O2}}{B-A} + b_2(p_{O1}-e)\frac{B-Z_{O3}}{B-A} \end{aligned}$$

$$\begin{vmatrix} \frac{\partial^2 E[\pi_{OR_2}]}{\partial Q_{O2}^2} & \frac{\partial^2 E[\pi_{OR_2}]}{\partial Q_{O2}\partial p_{O2}} \\ \frac{\partial^2 E[\pi_{OR_2}]}{\partial p_{O2}\partial Q_{O2}} & \frac{\partial^2 E[\pi_{DR_2}]}{\partial p_{O2}^2} \end{vmatrix}$$

$$= \begin{vmatrix} -\frac{(p_{O1}-e)m^2(\tau)\gamma_1^2}{B-A} & -\frac{b_2(p_{O1}-e)m(\tau)\gamma_1}{B-A} \\ -\frac{b_2(p_{O1}-e)m(\tau)\gamma_1}{B-A} & 2b_2\frac{B-Z_{D2}}{B-A} - \frac{b_2^2p_{O2}}{B-A} - \frac{b_2^2(p_{O1}-e)}{B-A} \end{vmatrix} < 0$$

So, as shown at the bottom of the next page.

The same can be obtained $Q_{O1}^{*} = \frac{B+a_1\theta(\tau)\varepsilon_1 - b_1 p_{O1}}{m(\tau)\gamma_1} - \frac{(w+c(\tau))(B-A)}{p_{O1}m^2(\tau)\gamma_1^2}$

$$p_{O1}^{*} = \frac{4b_1B - 4b_1K_{O1}}{6b_1^2} + \frac{\sqrt{(4b_1B-4b_1K_{O1})^2 + 12b_1^2(2BK_{O1} - K_{O1}^2 - A^2)}}{6b_1^2}$$

APPENDIX F

Proof of Corollary 6.

$$Q_O^{*} - Q_D^{*} = \frac{B - Q_{O1}m^2(\tau)\gamma_1\gamma_2 + d(p_1)m(\tau)\gamma_2 + d(p_2)}{m(\tau)\gamma_1} > 0,$$

$$Q_O^{*} - Q_C^{*} = \frac{B - Q_{O1}m^2(\tau)\gamma_1\gamma_2 + d(p_1)m(\tau)\gamma_2 + d(p_2)}{m(\tau)\gamma_1} + \frac{(c-w)(B-A)}{p_1 m^2(\tau)\gamma_1^2} > 0$$

APPENDIX G

Proof of Corollary 7. Because $K_{D1} < K_{O1} < K_{C1}$, then $p_{D1}^{*} > p_{O1}^{*} > p_{C1}^{*}$

Because $K_{D2} < K_{O2} < K_{C2} < K_{O3}$, $K_{O3} = K_{O2} + Q_{O2}m(\tau)\gamma_1$, $Z_{O3} = Z_{O2} + Q_{O2}m(\tau)\gamma_1$, then as shown at the bottom of the next page.

The same can be obtained as shown at the bottom of the next page.

so $p_{D2}^{*} > p_{O2}^{*} > p_{C2}^{*}$.

APPENDIX H

Proof of proposition 4.

$$w_O^{*} - w_D^{*} = \frac{(B + a_1\theta(\tau)\varepsilon_1 - b_1p_{O1})p_{O1}m(\tau)\gamma_1}{2(B-A)} - \frac{(B + a_1\theta(\tau)\varepsilon_1 - b_1p_{D1})p_{D1}m(\tau)\gamma_1}{2(B-A)} > 0$$

APPENDIX I

Proof of Corollary 8.Since $c(\tau)$ is a strictly increasing function on τ, by Corollary (5) we know that, $\tau^{*} = c^{-1}(w)$, when $w_O^{*} > w_D^{*}$, then we can obtain $\tau_O^{*} = c^{-1}(w_O) > \tau_D^{*} = c^{-1}(w_D)$.

APPENDIX J

Proof of Corollary 9. Since $E[\pi_{OS}]$ increases with o and e, $E[\pi_{OR}]$ decreases with o and e, $E[\pi_O]$ is a function without o and e.

APPENDIX K

Proof of proposition 5.

$$E[\pi_{OR}] = p_{O1}\frac{2Z_{O1}B - Z_{O1}^2 - A^2}{2(B-A)} - (w + c(\tau))Q_{O1} - oQ_{O2} + p_{O2}\frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} + (p_{O1} - e)\frac{2Z_{O3}B - Z_{O3}^2 - A^2}{2(B-A)}$$

Because $Q_O^{*} > Q_D^{*}$,then $Z_{O1} > Z_{D1}$,assumed $N = \frac{2ZB - Z^2 - A^2}{2(B-A)}$, $Z < B$, $\frac{\partial N}{\partial Z} = \frac{B-Z}{B-A} > 0$

$$p_{O1}\frac{2Z_{O1}B - Z_{O1}^2 - A^2}{2(B-A)} - p_{D1}\frac{2Z_{D1}B - Z_{D1}^2 - A^2}{2(B-A)} > 0$$

So $p_{O2}\frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} - p_{D2}\frac{2Z_{D2}B - Z_{D2}^2 - A^2}{2(B-A)} > 0$,

$$Q_{O1}^{*} - Q_D^{*} = \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1p_{O1}}{m(\tau)\gamma_1} - \frac{B + a_1\theta(\tau)\varepsilon_1 - b_1p_{D1}}{m(\tau)\gamma_1} - \frac{(w + c(\tau))(B-A)}{p_{O1}m^2(\tau)\gamma_1^2} + \frac{(w + c(\tau))(B-A)}{p_{D1}m^2(\tau)\gamma_1^2} = \frac{(p_{D1} - p_{O1})[b_1p_{O1}p_{D1}m(\tau)\gamma_1 - (w + c(\tau))(B-A)]}{p_{O1}p_{D1}m^2(\tau)\gamma_1^2 m(\tau)\gamma_1}$$

When p is an exogenous variable

$$E[\pi_{OR}] - E[\pi_{DR}] = p_{O1}\frac{2Z_{O1}B - Z_{O1}^2 - A^2}{2(B-A)} - p_{D1}\frac{2Z_{D1}B - Z_{D1}^2 - A^2}{2(B-A)} - oQ_{O2} + p_{O2}\frac{2Z_{O2}B - Z_{O2}^2 - A^2}{2(B-A)} - p_{D2}\frac{2Z_{D2}B - Z_{D2}^2 - A^2}{2(B-A)}$$

$$Q_{O2}^{*} = \frac{B - Q_{O1}m^2(\tau)\gamma_1\gamma_2 + a_1\theta(\tau)\varepsilon_1 m(\tau)\gamma_2 - b_1p_{O1}m(\tau)\gamma_2}{m(\tau)\gamma_1} + \frac{a_2m(\tau)\gamma_2 - b_2p_{O2}}{m(\tau)\gamma_1}$$

$$p_{O2}^{*} = \frac{4b_2B - 4b_2K_{O2} - 2b_2^2(p_{O1} - e)}{6b_2^2} + \frac{\sqrt{[4b_2B - 4b_2K_{O2} - 2b_2^2(p_{O1} - e)]^2 + 12b_2^2[2BK_{O2} - K_{O2}^2 - A^2 + 2b_2(p_{O1} - e)(B - K_{O3})]}}{6b_2^2}$$

$$+(p_{O1}-e)\frac{2Z_{O3}B-Z_{O3}^2-A^2}{2(B-A)}+(w+c(\tau))(Q_D-Q_{O1})>0$$

The retailer's expected profit under option contract is greater than that under decentralized decision.

$$E[\pi_{OS}]-E[\pi_{DS}]=(w-c)(Q_{O1}-Q_D)-cQ_{O2}+oQ_{O2}+e\frac{2Z_{O3}B-Z_{O3}^2-A^2}{2(B-A)}>0,$$

The producer's expected profit under option contract is greater than that under decentralized decision.

$$\begin{aligned}E[\pi_O]-E[\pi_D]&=p_{O1}\frac{2Z_{O1}B-Z_{O1}^2-A^2}{2(B-A)}-p_{D1}\frac{2Z_{D1}B-Z_{D1}^2-A^2}{2(B-A)}\\&+p_{O1}\frac{2Z_{O3}B-Z_{O3}^2-A^2}{2(B-A)}-c(\tau)Q_{O1}\\&+p_{O2}\frac{2Z_{O2}B-Z_{O2}^2-A^2}{2(B-A)}\\&-p_{D2}\frac{2Z_{D2}B-Z_{D2}^2-A^2}{2(B-A)}-c(Q_{O2}+Q_{O1})\\&+(c+c(\tau))Q_D>0\end{aligned}$$

APPENDIX L

Proof of proposition 6.

$$E[\pi_C]=p_{C1}\frac{2Z_{C1}B-Z_{C1}^2-A^2}{2(B-A)}-(c+c(\tau))Q_C+p_{C2}\frac{2Z_{C2}B-Z_{C2}^2-A^2}{2(B-A)}$$

Because $Q_O^*>Q_C^*>Q_{O1}^*$,then

$$Z_{C1}>Z_{O1},p_{C1}\frac{2Z_{C1}B-Z_{C1}^2A^2}{2(B-A)}-p_{O1}\frac{2Z_{O1}B-Z_{O1}^2-A^2}{2(B-A)}>0,$$

So, $p_{C2}\frac{2Z_{C2}B-Z_{C2}^2-A^2}{2(B-A)}-p_{O2}\frac{2Z_{O2}B-Z_{O2}^2-A^2}{2(B-A)}>0$,

$$\begin{aligned}\Delta=E[\pi_C]-E[\pi_O]&=p_{C1}\frac{2Z_{C1}B-Z_{C1}^2-A^2}{2(B-A)}\\&-p_{O1}\frac{2Z_{O1}B-Z_{O1}^2-A^2}{2(B-A)}\\&+c(Q_{O2}+Q_{O1})+c(\tau)Q_{O1}+p_{C2}\frac{2Z_{C2}B-Z_{C2}^2-A^2}{2(B-A)}\\&-p_{O2}\frac{2Z_{O2}B-Z_{O2}^2-A^2}{2(B-A)}-p_{O1}\frac{2Z_{O3}B-Z_{O3}^2-A^2}{2(B-A)}\\&-(c+c(\tau))Q_C>0\end{aligned}$$

$$\begin{aligned}&[4b_2B-4b_2K_{O2}-2b_2^2(p_{O1}-e)]^2\\&\quad+12b_2^2[2BK_{O2}-K_{O2}^2-A^2+2b_2(p_{O1}-e)(B-K_{O3})]\\&-(4b_2B-4b_2K_{D2})^2-12b_2^2(2BK_{D2}-K_{D2}^2-A^2)\\&=-16b_2^3(B-K_{O2})(p_{O1}-e)+24b_2^3(p_{O1}-e)(B-K_{O3})\\&=b_2^3(p_{O1}-e)(24B-24K_{O2}-24Q_{O2}m(\tau)\gamma_1-16B-16K_{O2})\\&=8b_2^3(p_{O1}-e)(B-K_{O2}-3Q_{O2}m(\tau)\gamma_1)\\&=8b_2^3(p_{O1}-e)(B-K_{O2}-3B+3K_{O2}+3b_2p_{O2})<0\end{aligned}$$

$$\begin{aligned}&p_{O2}^*-p_{D2}^*\\&=-\frac{2b_2^2(p_{O1}-e)}{6b_2^2}-\frac{\sqrt{(4b_2B-4b_2K_{D2})^2+12b_2^2(2BK_{D2}-K_{D2}^2-A^2)}}{6b_2^2}\\&+\frac{\sqrt{[4b_2B-4b_2K_{O2}-2b_2^2(p_{O1}-e)]^2+12b_2^2[2BK_{O2}-K_{O2}^2-A^2+2b_2(p_{O1}-e)(B-K_{O3})]}}{6b_2^2}\\&<0\\&p_{O2}^*<p_{D2}^*\end{aligned}$$

$$\begin{aligned}&p_{O2}^*-p_{C2}^*\\&=\frac{\sqrt{[4b_2B-4b_2K_{O2}-2b_2^2(p_{O1}-e)]^2+12b_2^2[2BK_{O2}-K_{O2}^2-A^2+2b_2(p_{O1}-e)(B-K_{O3})]}}{6b_2^2}\\&-\frac{\sqrt{(4b_2B-4b_2K_{C2})^2+12b_2^2(2BK_{C2}-K_{C2}^2-A^2)}-2b_2^2(p_{O1}-e)}{6b_2^2}>0\end{aligned}$$

APPENDIX M

Proof of proposition 7. When p and Q are exogenous.

$$
\begin{aligned}
\Delta &= E[\pi_C] - E[\pi_O] = c(\tau)(Q_1 - Q) \\
&\quad - p_1 \frac{2Z_{O3}B - Z_{O3}^2 - A^2}{2(B-A)} \\
\frac{\partial \Delta}{\partial \tau} &= c'(\tau)(Q_1 - Q) - p_1 \frac{B - Z_{O3}}{B-A}[Q_{O1}2m(\tau)m'(\tau)\gamma_1\gamma_2 \\
&\quad \times Q_{O2}m'(\tau)\gamma_1 - a_1\theta'(\tau)\varepsilon_1 m(\tau)\gamma_2 \\
&\quad - a_1\theta(\tau)\varepsilon_1 m'(\tau)\gamma_2 \\
&\quad + b_1p_1m'(\tau)\gamma_2 - a_2\theta'(\tau)\varepsilon_2 + b_2p_2] \\
\frac{\partial^2 \Delta}{\partial \tau^2} &= c''(\tau)(Q_1 - Q) - \frac{-p_1}{B-A}[Q_{O1}2m(\tau)m'(\tau)\gamma_1\gamma_2 \\
&\quad + Q_{O2}m'(\tau)\gamma_1 \\
&\quad - a_1\theta'(\tau)\varepsilon_1 m(\tau)\gamma_2 - a_1\theta(\tau)\varepsilon_1 m'(\tau)\gamma_2 + \\
&\quad + b_1p_1m'(\tau)\gamma_2 - a_2\theta'(\tau)\varepsilon_2 + b_2p_2] \\
&\quad + p_1 \frac{B - Z_{O3}}{B-A}[Q_{O1}2m'(\tau)m'(\tau)\gamma_1\gamma_2 \\
&\quad + Q_{O1}2m(\tau)m''(\tau)\gamma_1\gamma_2 \\
&\quad + Q_{O2}m''(\tau)\gamma_1 - a_1\theta''(\tau)\varepsilon_1 m(\tau)\gamma_2 \\
&\quad - a_1\theta''(\tau)\varepsilon_1 m'(\tau)\gamma_2 - a_1\theta'(\tau)\varepsilon_1 m'(\tau)\gamma_2 \\
&\quad - a_1\theta(\tau)\varepsilon_1 m''(\tau)\gamma_2 + b_1p_1m''(\tau)\gamma_2 \\
&\quad - a_2\theta''(\tau)\varepsilon_2 + b_2p_2] < 0
\end{aligned}
$$

Δ is a convex function with only one solution when $\frac{\partial \Delta}{\partial \tau} = 0$, then $\Delta = 0$. Assuming that the freshness-keeping effort is solved as $\tau = \tau^N$, when $\tau = \tau^N$, the option contract can achieve perfect coordination.

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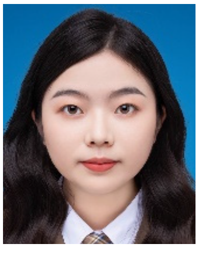

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