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RESEARCH ARTICLE

Dynamic Decision-Making in Fresh Products Supply Chain With Strategic Consumers

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ABSTRACT Fresh agricultural products constantly lose freshness during sales, and strategic consumers choose the optimal purchase timing according to the freshness and prices. In this paper, we introduce freshness-keeping effort to describe the retailer's freshness-keeping work and provide a consumer utility function to describe strategic behavior. Additionally, we construct a dynamic decision-making model using the rational expectations equilibrium to improve the profits of each member. This study also designs a freshness-keeping cost-sharing and revenue-sharing contract to coordinate the supply chain. Finally, we verified the effectiveness of the model by numerical simulation. The results show that optimal order quantity and freshness-keeping effort with strategic consumers are lower than without strategic consumers. Second, prices during normal and discount periods are both positively correlated with valuation. In addition, the normal price is negatively correlated with order quantity and freshness-keeping effort, and the discount price is positively correlated with order quantity. The correlation between discount price and freshness-keeping effort has a critical value, and the discount price is positively correlated with freshness-keeping effort when below the critical effort, and negatively after exceeding the critical effort. Third, the combination contract can increase expected profits for both supplier and retailer and help the decentralized supply chain achieve the expected profits of the centralized supply chain.

INDEX TERMS Fresh agricultural products, freshness-keeping effort, strategic consumers, dynamic decision-making, rational expectations equilibrium, supply chain coordination.

I. INTRODUCTION

In recent years, fresh agricultural products have become essential for daily consumption, and their freshness directly affects health. These mainly include fruits, vegetables, poultry and their products, flowers, livestock, and aquatic products. Owing to the short life cycle of products and uncertain market demands, retailers face the risk of stagnation or being out of stock and suffering huge losses [1], [2], [3]. Consumers are unwilling to pay full price for stale products, and their desire for products is crucial to the supply chain. As a result, retailers have to make decisions different from those for durable goods. Keeping freshness is the key to minimizing the loss of fresh agricultural products. Such freshness-keeping work is mainly expressed as freshness-keeping effort, which supply chain members need to decide to retain products' freshness [4]. The research on supply chain management and coordination of fresh agricultural products has been widely discussed by the business community and academia. Strengthening the design of the supply chain is the key to fresh retail development.

With the upgrade of people's living standards, the demand for high-quality products is gradually increasing. Measures such as freshness-keeping and discounts are taken to satisfy consumer demand, but they can also create strategic choice behavior. Throughout the selling process, consumer utility varies with freshness and prices. Strategic consumers compare the consumer surplus in different sales periods and choose the optimal purchase time to maximize the utility. In addition, the dynamic decision-making of the supply chain

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has been widely concerned. Many fresh supermarkets set different prices at different periods. For example, after twenty o'clock, retailers reduce the price to promote sales, because after one night, the freshness of the next day will reach a new low. Therefore, different prices are set according to freshness and order quantity to reduce the losses. Therefore, combine the characteristics of fresh agricultural products and strategic consumer behavior to make dynamic decisions in the supply chain. This would be an interesting topic to explore.

Based on the above background, retailer need to respond to consumers' strategic choice behavior and make optimal pricing and ordering decisions when faced with uncertain demand. The retailer also signs appropriate contracts with supplier to share benefits and risks. In this study, we address the following fundamental questions:

- How do the three supply chain members, including supplier, retailer, and strategic consumers, make optimal decisions in different sales periods?
- How do consumers strategically influence the optimal decisions in the fresh agricultural products supply chain?
- What is the optimal order quantity, prices, and freshness-keeping effort? Further, how do different valuation and freshness-keeping effort affect pricing?
- What types of contracts can increase the expected profits and coordinate the supply chain? How does the combination contract affect the fresh agricultural products supply chain making optimal decisions?

We study how to obtain optimal decisions in the case of random demand and different freshness and develop pricing and ordering strategies for fresh agricultural products to maximize profits.

This study has the following significance in both theory and practice. Many scholars have done extensive research on the fresh agricultural products supply chain. But, most of the research is aimed at short-sighted consumers or does not consider the influence of consumers. As buyers, the study of consumers' strategic behavior for different freshness and prices is helpful to improve the relevant research on dynamic decision-making of fresh products supply chain and help us better understand the impact of different consumption behaviors on the supply chain. Our understanding of the dynamic study of fresh agricultural products has been strengthened through modeling analysis and numerical simulation. Further, through the in-depth analysis, the corresponding adjustment and improvement measures are proposed. This can improve the coordination effect of the supply chain, reduce the negative impact of strategic consumers, and increase the competitiveness of the fresh agricultural supply chain in the retail market.

The following is the remainder of this study. Section II examines and analyzes the relevant literature. Section III describes and hypothesizes strategic consumer behavior and retailer freshness-keeping behavior in the fresh agricultural products supply chain. Section IV establishes a dynamic decision-making model under a centralized supply chain based on the traditional newsboy model. Section V analyzes supply chain decision-making in decentralized situation. Section VI analyzes the role of freshness-keeping cost-sharing and revenue-sharing contract in supply chain coordination. Section VII performs numerical simulations and analysis. Section VIII concludes with a discussion of the results.

II. LITERATURE REVIEW

The research related to this study is mainly divided into three parts. In the first part, many scholars have studied freshness-keeping effort and supply chain contract design. In the second part, many scholars have studied the dynamic decision-making strategies in the supply chain of fresh agricultural products. Some studies adopted fresh-keeping measures, and some studies adopted dynamic pricing, which can reduce the impact of freshness decline. In the third part, many scholars have researched strategic consumers, some of which introduce rational expectations equilibrium to establish a relationship between consumers' strategic behavior and retailer's strategies. Consumers are strategic when making purchase choices in daily life, and they choose the best purchase time to maximize their utilities. This strategic behavior will directly affect demand. Therefore, the influence of consumers' strategic behavior cannot be ignored.

Relevant literature for freshness-keeping effort and supply chain contract design. Cai et al. [4] argued that providing freshness-keeping effortcan reduce quality and quantity losses during transportation. They established a model to explore the optimality of centralized and decentralized decision-making and further introduced incentives to achieve the coordination of a fresh agricultural supply chain. Gu et al. [5] verified that supply chain profits can be improved by providing freshness-keeping effort when consumers are loss-averse. Then, they designed a revenue- and cost-sharing contract and compared the effectiveness of different contracts, finding that each supply chain member can achieve higher expected profits under the buybackand the new combination contracts than under the wholesale price contract. In addition to the buyback and wholesale price contracts mentioned in the above literature, there are many other common contracts in the research. Examples include quantity flexibility contract [6], revenue sharing contract [7], [8], cost sharing contract [9], [10], quantity discount contract [11], option contract [12], [13], and sales rebate contract [14]. The study found that these contracts can help improve supply chain performance [4], [15], [16].

Relevant literature for dynamic decision-making strategies in the supply chain of fresh agricultural products. Fan et al. [17] explored multi-batch dynamic pricing and four heuristic replenishment strategies for fresh products. They concluded that order quantity is related to the freshness and the remaining stock and decreases as initial freshness increases. Herbon et al. [18] and Li et al. [19] studied the dynamic pricing of perishables containing fresh agricultural

TABLE 1. Summary of relevant literature.

Authors	Fresh agricultural products	Freshness-keeping effort	Contract coordination	Dynamic pricing	Strategic consumers	Rational expectations equilibrium
Cai et al. [4]	•	•	•			
Gu et al. [5]	•	•	•			
Zhao and Cheng[12]	•	•	•	•		
Fan et al. [17]	•			•	•	
Dong and Dash[23]				•	•	
Levin et al.[24],[25]	•			•	•	
Qiu et al. [27]	•		•	•	•	
Su and Zhang [28]					•	•
Yan et al. [15]	•		•	•	•	•
Quan et al.[31]					•	•
Zhang et al.[32]				•	•	•
This work	•	•	•	•	•	•

products from different perspectives. Herbon et al. [18] analyzed dynamic pricing and optimal replenishment strategies for perishable products whose demand is influenced by time and price. Li et al. [19] studied a joint dynamic pricing and batch model for perishable products, where demand is affected by the selling and reference prices and limited by inventory level and freshness. Significantly, Zhao and Cheng [12] studied a two-stage fresh products supply chain with quality and quantity loss. They not only considered dynamic decision-making but also discussed the effects of freshness-keeping effort. Finally, they designed option contract and verified the effectiveness of contract coordination.

Relevant literature for strategic consumers. Case [20] was the first to theorize the influence of consumers on demand. Then Cachon et al. [21] classified consumers as strategic, short-sighted, and bargaining according to their behavior and found that strategic consumers would reduce supply chain performance. Similarly, Du et al. [22] also concluded that strategic consumers are harmful to retailers' profits. In addition, some related literature studied strategic consumers and dynamic decision-making, such as [23], [24], [25], and [26]. Notably, Qiu et al. [27] studied strategic consumers and dynamic decision-making and considered contract design. They analyzed a two-stage decision model, which considered transportation loss and retail quality loss under strategic consumers. Then, they introduced revenue and service costs sharing contract that can achieve supply chain coordination. However, Qiu et al. regarded order quantity and demand as the same variable. There is a comparison between the two variables, just like the newsboy model.

So we introduced rational expectations equilibrium to make the model more realistic. Because Su and Zhang [28] argued that consumers cannot get the inventory precisely and can only make strategic decisions based on rational expectations. The rational expectations hypothesis was first proposed in 1961 and was widely used in the economic field. It assumed that the results of economic operations do not deviate systematically from people's expectations. Later, Su and Zhang [28], [29], [30] introduced the rational expectations hypothesis into supply chain management. They used rational expectations equilibrium based on the traditional newsboy model and analyzed the behaviors of strategic consumers, such as valuation, waiting, inertia, and speculation. In addition, some scholars have studied some commitments to strategic consumers, such as quantity commitment [28], [31], and price commitment [32]. The adoption of contracts and commitments can both help improve supply chain efficiency. Significantly, Yan et al. [15] quantified consumers' strategic behavior as risk aversion coefficients, and then they introduced rational expectations equilibrium to solve and analyze the influence of consumers' risk attitude on supply chain decision-making. They also designed wholesale price and revenue sharing contracts.

In summary, Table 1 shows the comparison between relevant literature and this work, which is more visible. We can find that some scholars have studied fresh-keeping effort and dynamic decision-making but did not consider strategic consumers' influence. Some scholars have studied dynamic decision-making and contract design of fresh products supply chain under strategic consumers but did not consider the impact of the freshness-keeping effort. Therefore, we consider both fresh agricultural products' freshness-keeping effort and dynamic decision-making under strategic consumers to fill this gap.

The novelty of this study can be divided into two categories. First, the research content is novel. As for dynamic decision-making in fresh agricultural products supply chain under strategic consumers, existing studies have only considered the impact of freshness on consumers' strategic behavior when demand and order quantity are not considered as a variable but have not further considered the relationship between freshness and freshness-keeping effort. Therefore, unlike previous studies, the novelty of this study is introducing freshness-keeping effort to describe the freshness-keeping work of retailers and focusing on the impact of freshness-keeping effort during the sales period. Second, the research method is novel. We introduce rational expectations equilibrium to describe and construct the dynamic decision and coordination of the newsboy model.

TABLE 2. Notations.

Symbol	Description
Q_i^C	stock quantity of period i, i=1.2.3under centralized decision-making (a decision variable)
Q_i^D	stock quantity of period i, i=1.2.3 under decentralized decision-making (a decision variable)
Q_i^0	The optimal stock quantity without strategic consumer(a decision variable)
p_i^C	Selling price of period i, i=1.2under centralized decision-making (a decision variable)
p_i^D	Selling price of period i, i=1.2 under decentralized decision-making (a decision variable)
p_i^{RC}	Selling price of period i under combination contract (a decision variable)
τ	The retailer's freshness-keeping effort (a decision variable)
c	Unit production cost of the supplier, $c>s$
$c(\tau)$	Freshness-keeping cost function
w	Unit wholesale price, $w>c$
θ_0	Initial freshness
$\theta_i(\tau)$	Freshness function for period i, i=1.2.3
c_0	Freshness-keeping cost factor
V	Consumer valuation of products
$E\theta(\tau)$	The elasticity function of $\theta(\tau)$
$Ec(\tau)$	The elasticity function of $c(\tau)$
U_i	Consumer utility function of period i, i=1.2.3
s	The unit clearance price
D_i	The market demand of period i, i=1.2.3
$E[\pi_r]$	The retailer's expected profit function under decentralized decision-making
$E[\pi_s]$	The supplier's expected profit function under decentralized decision-making
$E[\pi_i^C]$	The expected profit function of period i under centralized decision-making, i=1.2.3
$E[\pi_i^D]$	The expected profit function of period i under decentralized decision-making, i=1.2.3
$E[\pi_i^{RC}]$	The expected profit function of period i under combination contract, i=1.2.3

III. NOTATIONS AND ASSUMPTIONS

Faced with uncertain demand, the supplier, retailer, and strategic consumers in the fresh agricultural products supply chain make dynamic decisions. Fresh agricultural products undergo one order and two price reductions during the three sales periods: the normal, discount, and clearance periods.

Before the selling season, the retailer decides the order quantity after considering the consumers' strategic behavior and wholesale price and then decides on selling prices and freshness-keeping effort. At the beginning of the normal period, the strategic consumers decide the optimal timing of purchases to maximize the expected utility, with the probability of obtaining products in the discount period. During the discount period, the retailer sells products at a reduced price as freshness declines, while strategic consumers consider the probability of getting products in the clearance period and choose to buy immediately or continue to wait. During the clearance period, the retailer liquidates the remaining products to minimize losses, and strategic consumers decide to purchase or leave.

Assume that consumers are strategic and risk-neutral. Fresh agricultural products have zero residual value at the end of the clearance period. Referring to [33] and [34], we assume that costs except production and freshness-keeping costs are standardized to 0. For the retailer to make a profit, suppose $p_1 > c + c(\tau)$.

The retailer decides the initial order quantity Q_1 and selling prices p_1, p_2 after considering the wholesale price and strategic consumer behavior. Moreover, we assume that the demands $D_i, i = 1, 2, 3$ in the three selling periods are independent of each other and follow a normal distribution. The cumulative distribution function and probability density function of demands are $F_i(\bullet), f_i(\bullet), i = 1, 2, 3$. As the products are near the end of their life cycle, the third sales period deals with the remaining products at the clearance price s. Strategic consumers are independent in their respective decisions, and value the products at the beginning of the normal periodas V. As the freshness of fresh products decreases, so do the valuation and prices. Hence, we assume that $V_i = \theta_i(\tau)V, i = 1, 2, 3$ and $p_1 > p_2 > s$.

Because the inventory level is not publicized, strategic consumers need to estimate the probability of getting products in the following period. Therefore, referring to [15] and [28], we assume the probability of getting products is $\xi_i, i = 1, 2, 3$, where $\xi_1 = 1$. We refer to the utility function model proposed in the literature [14] and consider that strategic consumers have different expected utilities for fresh agricultural products with different freshness, and the expected utility functions of consumers in the three selling periods are $U_1 = V_1 - p_1, U_2 = (V_2 - p_2)\xi_2, U_3 = (V_3 - s)\xi_3$. In addition, we assume that consumers buy only if the utility function is non-negative. So that $U_i \geqslant 0$, and then we get $V_i \geqslant p_i, i = 1, 2, 3$. Finally, combined with the assumption $w > c$ and $c > s$, we know that $V_1 \geqslant p_1 > p_2 > w > c > s$.

The retailer applies the freshness-keeping effort of $\tau, \tau \in [\tau^l, \tau^u]$, where τ^l and τ^u denote the minimum and maximum freshness-keeping effort, respectively. To mitigate the deterioration during the normal and discount periods, we assume that the unit freshness-keeping cost function is $c(\tau)$, and the freshness function is $\theta(\tau)$, $\theta(\tau) \in (0, 1]$. Here, $\theta(\tau)$ and $c(\tau)$ are monotonically increasing functions of τ, they indicate that the unit freshness and freshness-keeping cost of products increase with freshness-keeping effort. In fact, according to the decay characteristics of the products, the increased rate of freshness decreases while the increased rate of freshness-keeping cost increases, so $\theta'(\tau) > 0, c'(\tau) > 0, \theta''(\tau) < 0, c''(\tau) > 0$.

Referring to the literature [4], we introduce the elasticity function $Es(x) = s'(x)x/s(x)$, where $s(x)$ is continuously monotonically increasing, and the elasticity function $s(x)$ measures the percentage increase in the function when x increases 1%. The elasticity functions of $\theta(\tau)$ and $c(\tau)$ can be expressed as $E\theta(\tau) = \theta'(\tau)\tau/\theta(\tau)$ and $Ec(\tau) = c'(\tau)\tau/c(\tau)$. In this study, $E\theta(\tau)$ and $Ec(\tau)$ are treated as constants. Then, we can obtain $\theta(\tau) = \theta_0\tau^{E\theta(\tau)}, c(\tau) = c_0\tau^{Ec(\tau)}\,(c_0 > 0)$, where $E\theta(\tau) \in (0, 1), Ec(\tau) \in [1, +\infty)$. Based on this, we assume that the freshness of products are $\theta_i(\tau) = \theta(\tau)^{i-1}, i = 1, 2, 3$, and the freshness functions for the three periods are $\theta_1(\tau) = [\theta_0\tau^{E\theta(\tau)}]^0 = 1, \theta_2(\tau) = \theta_0\tau^{E\theta(\tau)}$, and $\theta_3(\tau) = [\theta_0\tau^{E\theta(\tau)}]^2$.

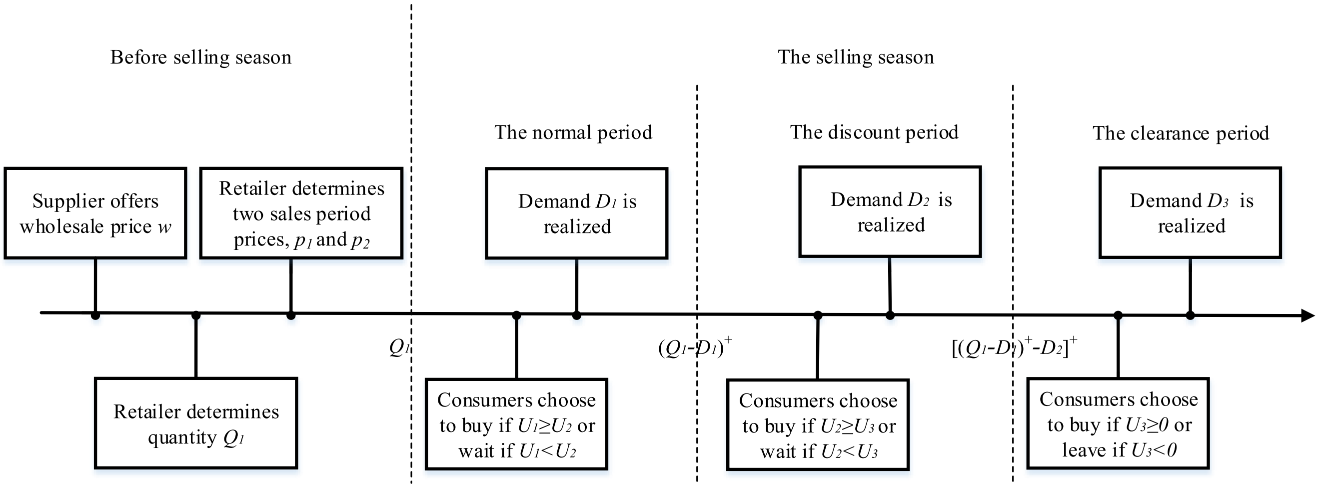

FIGURE 1. **Timeline of events under consideration.**

IV. CENTRALIZED DECISION-MAKING MODEL

A. DECISION-MAKING MODEL

Strategic consumers want to maximize the expected utility when buying fresh agricultural products. They consider the freshness and price mechanism and choose the optimal purchase time. Referring to [7] and [15], we conduct modeling and analysis following the reverse process.

Strategic consumers make purchase decisions based on the clearance price when the consumer surplus is V_3-s. Because of the limited and unannounced stock in real life, strategic consumers form beliefs ξ_3 about the probability of getting products during the clearance period. At the same time, consumers also have the probability of being unable to obtain fresh agricultural products. Referring to reference [17], we assume that there is no expected loss of utility for strategic consumers who do not obtain the products, i.e., $U_0 = 0$. The expected utility of the strategic consumers during the clearance period can be expressed as

$$\max\{(V_3 - s)\xi_3 + U_0(1 - \xi_3), 0\}. \tag{1}$$

From Equation, strategic consumers buy fresh agricultural products immediately during the clearance period when $(V_3-s)\xi_3 \geqslant 0$, and they choose to leave when $(V_3 - s)\xi_3 < 0$.

The expected profits during the clearance period are:

$$E[\pi_3^C] = E\{s \min[(Q_2 - D_2)^+, D_3]\}. \tag{2}$$

Based on the characteristics of the fresh agricultural products supply chain, let $T = D_2 + D_3$ obeys the normal distribution that the distribution function is $G(\bullet)$ and the density function is $g(\bullet)$, so can be written as

$$E[\pi_3^C] = s\int_0^{Q_2} F_2(x_2)dx_2 - s\int_0^{Q_2} G(t)dt. \tag{3}$$

The consumer expected utility in the discount period can be expressed as

$$\max\{(V_2 - p_2)\xi_2 + U_0(1 - \xi_2), (V_3 - s)\xi_3 + U_0(1 - \xi_3)\}. \tag{4}$$

From Equation, strategic consumers choose to buy immediately when $(V_2 - p_2)\xi_2 \geqslant (V_3 - s)\xi_3$, and choose to wait when $(V_2 - p_2)\xi_2 < (V_3 - s)\xi_3$. From the marginal condition $(V_2-p_2)\xi_2 = (V_3-s)\xi_3$, we obtain the consumers' reservation price in the discount period as follows:

$$R_2 = V_2 - (V_3 - s)\xi_3/\xi_2.$$

where R_i is the critical value that maximizes the expected utility, and strategic consumers choose to buy immediately only if $p_i \leqslant R_i$.

The expected profits of the supply chain in discount period are as follows:

$$E[\pi_2^C] = E\{p_2 \min[(Q_1 - D_1)^+, D_2] - c(\tau)(Q_1 - D_1)^+\} + E[\pi_3^C]. \tag{5}$$

Let $M = D_1 + D_2$ obeys the normal distribution that the distribution function is $H(\bullet)$ and the density function is $h(\bullet)$. Let $X = D_1+D_2+D_3$ obeys the normal distribution that the distribution function is $F(\bullet)$ and the density function is $f(\bullet)$. So can be written as

$$E[\pi_2^C] = [p_2 - c(\tau)]\int_0^{Q_1} F_1(x_1)dx_1 - s\int_0^{Q_1} F(x)dx - (p_2 - s)\int_0^{Q_1} H(m)dm. \tag{6}$$

The expected utility of consumers in normal period can be expressed as

$$\max\{(V_1 - p_1)\xi_1 + U_0(1 - \xi_1), (V_2 - p_2)\xi_2 + U_0(1 - \xi_2)\}. \tag{7}$$

From Equation, strategic consumers will decide to buy immediately when $(V_1 - p_1)\xi_1 \geqslant (V_2 - p_2)\xi_2$, and wait for a price reduction when $(V_1 - p_1)\xi_1 < (V_2 - p_2)\xi_2$. From the marginal condition $(V_1-p_1)\xi_1 = (V_2-p_2)\xi_2$, the reservation price of strategic consumers in normal period is obtained as

$$R_1 = V_1 - (V_2 - p_2)\xi_2.$$

The expected profits of the supply chain in normal period are:

$$\begin{aligned}E[\pi^C] &= E\{p_1 \min(Q_1, D_1) - [c + c(\tau)]Q_1\} + E[\pi_2^C] \\ &= [p_2 - p_1 - c(\tau)] \int_0^{Q_1} F_1(x_1)dx_1 - s \int_0^{Q_1} F(x)dx \\ &\quad - (p_2 - s) \int_0^{Q_1} H(m)dm + [p_1 - c - c(\tau)]Q_1. \end{aligned} \tag{8}$$

Strategic consumers decide to buy immediately, wait, or leave by comparing the expected utility of the i period with that of the $i+1$ period.

For rational expectations equilibrium, we need to satisfy three conditions when making optimal decisions. First, strategic consumers decide the optimal purchase time based on the probability of obtaining products in the next period. Second, the retailer in a centralized supply chain decides the selling prices and order quantity based on the reservation price of strategic consumers. Third, the expectations of strategic consumers and retailer are consistent with the actual results.

We define the following equation based on the rational expectations equilibrium theory:

(1) $R_1 = V_1 - [V_2 - p_2]\xi_2, R_2 = V_2 - [V_3 - s]\xi_3/\xi_2$.
(2) $p_1 = R_1, p_2 = R_2, Q_1 = \arg_{Q_1>0}^{\max} \pi$.
(3) $\xi_2 = F_1(Q_1), \xi_3 = \mathrm{H}(Q_1)$.

where (1) means that strategic consumers make rational decisions based on expectations to obtain the maximum expected utility. (2) means that the retailer in a centralized supply chain determines the optimal order quantity and selling prices based on the expectation of maximizing profits. (3) means that the rational expectations are consistent with the actual situation. We focus on pricing and ordering decisions under the rational expectations equilibrium. When the sales prices and order quantity satisfy the conditions mentioned above, strategic consumers will choose to buy at the optimal time.

B. OPTIMAL DECISION ANALYSIS

Proposition 1: The optimal decisions of the centralized supply chain are as follows:

(1) The optimal order quantity is determined by the following equation:

$$\begin{aligned}&[\theta(\tau)V - V - c(\tau)]F_1(Q_1^{C^*}) - [\theta(\tau)V - s]H(Q_1^{C^*}) \\ &\quad + [\theta^2(\tau)V - s]H(Q_1^{C^*})[-2 + F_1(Q_1^{C^*}) + H(Q_1^{C^*})/F_1(Q_1^{C^*})] \\ &\quad - sF(Q_1^{C^*}) + V - c - c(\tau) = 0. \end{aligned} \tag{9}$$

(2) The optimal prices are as follows:

$$p_1{}^{C^*} = V - [\theta^2(\tau)V - s]H(Q_1^{C^*}), \tag{10}$$
$$p_2{}^{C^*} = \theta(\tau)V - [\theta^2(\tau)V - s]H(Q_1^{C^*})/F_1(Q_1^{C^*}). \tag{11}$$

(3) When the order quantity is certain, the optimal freshness-keeping effort can be derived as follows:

$$\tau^{C^*} = \begin{cases} \tau^l, & \text{if } \tau^0 \leqslant \tau^l \\ \tau^0, & \text{if } \tau^l < \tau^0 < \tau^u \\ \tau^u, & \text{if } \tau^0 \geqslant \tau^u. \end{cases}$$

When $\partial E[\pi^C]/\partial\tau = 0$, $\tau = \tau^0$. In order to make $E[\pi^C]$ strictly concave with τ, this paper discusses the case of $E\theta(\tau) \in (0.5, 1)$. The freshness-keeping effort is not the higher, the better, and it needs to be controlled within a certain range. When the freshness-keeping effort is low, improving effort can increase the expected profits. However, when over a critical value, continuing to improve the freshness-keeping effort not only cannot maintain the completeness of the products but also needs to pay high freshness-keeping costs.

The proof of Proposition 1 is provided in Appendix A.

In response to rational behavior, the supply chain adopts a reservation price pricing strategy, that is $p_i = R_i$. In addition, without strategic consumers, the short-sighted consumers choose to purchase when satisfying the consumer surplus $V_i - p_i \geqslant 0$. The supply chain adopts a valuation pricing strategy, that is $p_1{}^{0^*} = V_1 = V, p_2{}^{0^*} = V_2 = \theta(\tau)V$.

Corollary 1: The optimal order quantity with strategic consumers is less than without strategic consumers, i.e., $Q_1^{C^*} < Q_1^{0^*}$.

The proof of Corollary 1 is provided in Appendix B.

Strategic consumers can be motivated to purchase by reducing the order quantity. Because when strategic consumers focus on fewer products, they choose to buy earlier by judging that the probability of obtaining products in the next period is lower. Therefore, some products are sold at a higher price and do not bear the high freshness-keeping cost, which reduces the loss of profits caused by consumers' strategic behavior.

V. DECENTRALIZED DECISION-MAKING MODEL

Unlike centralized supply chain that focus on the overall effect, members of decentralized supply chain make decisions based on maximizing their expected profits.

A. RETAILER's DECISION-MAKING MODEL

The retailer's expected profits are:

$$\begin{aligned}E[\pi_r{}^D] &= [p_2{}^D - p_1{}^D - c(\tau)] \int_0^{Q_1{}^D} F_1(x_1)dx_1 \\ &\quad - s\int_0^{Q_1{}^D} F(x)dx - (p_2 - s)\int_0^{Q_1{}^D} H(m)dm \\ &\quad + [p_1{}^D - w - c(\tau)]Q_1{}^D. \end{aligned}$$

Proposition 2: The optimal decisions of decentralized supply chain are as follows:

(1) The optimal order quantity is determined by the following equation:

$$\begin{aligned}&[\theta(\tau)V - V - c(\tau)]F_1(Q_1^{D^*}) - [\theta(\tau)V - s]H(Q_1^{D^*}) \\ &\quad + [\theta^2(\tau)V - s]H(Q_1^{D^*})[-2 + F_1(Q_1^{D^*})\end{aligned}$$

$$+H(Q_1^{D^*})/F_1(Q_1^{D^*})] - sF(Q_1^{D^*}) + V - w - c(\tau) = 0. \tag{12}$$

(2) The optimal prices are as follows:

$$p_1{}^{D^*} = V - [\theta^2(\tau)V - s]H(Q_1^{D^*}), \tag{13}$$

$$p_2{}^{D^*} = \theta(\tau)V - [\theta^2(\tau)V - s]H(Q_1^{D^*})/F_1(Q_1^{D^*}). \tag{14}$$

(3) When the order quantity is certain, the retailer's optimal freshness-keeping effort can be derived as follows:

$$\tau^{D^*} = \begin{cases} \tau^l, & \text{if } \tau^0 \leqslant \tau^l \\ \tau^0, & \text{if } \tau^l < \tau^0 < \tau^u \\ \tau^u, & \text{if } \tau^0 \geqslant \tau^u. \end{cases}$$

When $\partial E[\pi^D]/\partial \tau = 0$, $\tau = \tau^0$.

The proof of Proposition 2 is similar to Appendix A.

Proposition 3: When the freshness-keeping effort τ is certain,

(1) $\partial p_1{}^D/\partial Q_1^D < 0$, $\partial p_2{}^D/\partial Q_1^D > 0$,
(2) $\partial p_1{}^D/\partial V > 0$, $\partial p_2{}^D/\partial V > 0$.

The proof of Proposition 3 is provided in Appendix C.

When freshness-keeping effort and valuation are certain, as the order quantity increases, the normal price decreases and the discount price increases. More strategic consumers choose to wait as the order quantity increases. Because the more products there are, the greater the probability of obtaining products in discount period. To promote strategic consumers buy immediately, the retailer should sell products at a lower price in normal period. In addition, as the order quantity increases, the higher discount price can encourage strategic consumers to buy earlier.

When the order quantity and freshness-keeping effort are certain, the higher the valuation of fresh products, the higher the prices that the retailer can set. The high valuation of products leads to high consumer utility, and strategic consumers are willing to buy at a high price.

Proposition 4: When the valuation V is certain,

(1) $\partial p_1{}^D/\partial \tau < 0$.
(2) If $\tau < [F_1(Q_1{}^D)/2\theta_0 H(Q_1{}^D)]^{1/E\theta(\tau)}$, $\partial p_2{}^D/\partial \tau > 0$, if $\tau > [F_1(Q_1{}^D)/2\theta_0 H(Q_1{}^D)]^{1/E\theta(\tau)}$, $\partial p_2{}^D/\partial \tau < 0$.
(3) $\partial Q_1{}^D/\partial \tau < 0$, when$F^2(Q_1^{D^*}) < H(Q_1^{D^*})$.

The proof of Proposition 4 is provided in Appendix D.

When valuation and order quantity are certain,the normal price is negatively related to freshness-keeping effort. To satisfy consumers' demand for high quality and low prices, we introduce freshness-keeping effort and dynamic pricing. However, those leads to greater choice for strategic consumers, and fresh products in discount period suffer less losses and lower price. More consumers may choose to wait, resulting in a decreased demand in the normal period. In response, the retailer can incentivize consumers during the normal period by reducing price.

The effect of the freshness-keeping effort on discount price is divided into two parts. The relationship between freshness-keeping effort and the discount price is positive when effort is lower and negative when effort exceeds a critical value because there is a shift in demand. As freshness-keeping effort increases and losses of freshness decrease, some of the demand in the normal period shifts to the discount period, with a consequent increase in discount price. Similarly, when the freshness-keeping effort exceeds a critical value, some demand in the discount period shifts to the clearance period. This leads to a decrease in discount price.

In addition to motivating consumers to buy immediately, the retailer can also promote consumption by reducing order quantity. Fewer products lead strategic consumers to believe that they are less likely to obtain the products if they do not buy them immediately. This prompts strategic consumers to make purchasing decision during normal or discount period. Therefore, we must explore the effect of freshness-keeping effort on prices and order quantity in sales periods to maximize expected utility and find the optimal decisions for the fresh agricultural products supply chain.

B. SUPPLIER's DECISION-MAKING Model

The supplier's expected profits are:

$$E[\pi_s{}^D] = (w - c)Q_1^D.$$

The dynamic process of the decentralized supply chain refers to centralized, and the total expected profits are the sum of the retailer's profits and the supplier's profits. Therefore, the total expected profits of the decentralized supply chain are:

$$\begin{aligned} E[\pi^D] &= E[\pi_r{}^D] + E[\pi_s{}^D] \\ &= [p_2{}^D - p_1{}^D - c(\tau^D)] \int_0^{Q_1{}^D} F_1(x_1)dx_1 \\ &\quad + [p_1{}^D - c - c(\tau^D)]Q_1{}^D \\ &\quad - s\int_0^{Q_1{}^D} F(x)dx - (p_2{}^D - s)\int_0^{Q_1{}^D} H(m)dm. \end{aligned}$$

C. COMPARISON OF CENTRALIZED AND DECENTRALIZED DECISION-MAKING

Proposition 5: The optimal decisions of centralized and decentralized supply chain are compared as follows:

(1) $Q_1^{D^*} < Q_1^{C^*}$.
(2) $p_1{}^{D^*} > p_1{}^{C^*}$, $p_2{}^{D^*} > p_2{}^{C^*}$,
(3) $\pi^{D^*} < \pi^{C^*}$.

The proof of Proposition 5 is provided in Appendix E.

Comparing centralized and decentralized supply chain, we find that decentralized supply chain has lower order quantity, higher prices, and lower profits, all of which verify the conclusions of the existing literature. These conclusions are consistent with the reality. The higher the normal price, the lower the willingness of strategic consumers to buy immediately. In decentralized supply chain, the supplier and retailer decide to maximize their respective benefits. The retailer sets a higher price and lower order quantity, which makes the profits always lower than centralized and does not maximize the efficiency of the supply chain.

Therefore, it is necessary to introduce suitable contract to motivate cooperation among supply chain members and improve the total profits. In this study, we introduce a freshness-keeping cost-sharing and revenue-sharing contract to maximize the profits of all parties and the total profits in decentralized supply chain.

VI. FRESHNESS-KEEPING COST-SHARING AND REVENUE-SHARING CONTRACT

In this section, we coordinate the supply chain of fresh agricultural products by designing a contract. First, the supplier offers a lower wholesale price, which motivates the retailer to reduce the selling prices during the normal and discount periods to promote consumption. Then, the retailer and supplier share the profits and freshness-keeping costs. Furthermore, the role of this contract is noteworthy.

To meet consumers' demand for fresh products, the retailer undertakes freshness-keeping effort and selects appropriate levels. However, the retailer's incentive for freshness-keeping is low because of the high freshness-keeping cost and consumers' strategic behavior. Therefore, we analyze the role of freshness-keeping cost-sharing and revenue-sharing contract in supply chain coordination.

The retailer bears the freshness-keeping cost ratio of $\varphi \in [0, 1]$, and the supplier shares the freshness-keeping cost ratio of $(1 - \varphi)$. At the same time, the retailer enjoys the revenue ratio of $\lambda \in [0, 1]$, and shares the revenue ratio of $(1 - \lambda)$ with the supplier.

The retailer's expected profits are:

$$E[\pi_r{}^{RC}] = [\lambda p_2{}^{RC} - \lambda p_1{}^{RC} - \varphi c(\tau)] \int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 - \lambda(p_2{}^{RC} - s) \int_0^{Q_1{}^{RC}} H(m)dm - \lambda s \int_0^{Q_1{}^{RC}} F(x)dx + [\lambda p_1{}^{RC} - w - \varphi c(\tau)]Q_1{}^{RC}.$$

The supplier's expected profits are:

$$E[\pi_s{}^{RC}] = (w - c)Q_1{}^{RC} + (1 - \lambda) \times [(p_2{}^{RC} - p_1{}^{RC}) \int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 - \left(p_2{}^{RC} - s\right) \int_0^{Q_1{}^{RC}} H(m)dm - s \int_0^{Q_1{}^{RC}} F(x)dx + p_1{}^{RC}Q_1{}^{RC}] - (1 - \varphi)c(\tau)[\int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 + Q_1{}^{RC}].$$

The total profits under contractual coordination are:

$$E[\pi^{RC}] = [p_2{}^{RC} - p_1{}^{RC} - c(\tau)] \int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 - s \int_0^{Q_1{}^{RC}} F(x)dx - \left(p_2{}^{RC} - s\right) \int_0^{Q_1{}^{RC}} H(m)dm + [p_1{}^{RC} - c - c(\tau)]Q_1{}^{RC}.$$

Proposition 6: when φ/λ is certain, the optimal order quantity Q_1^{RC*} is negatively correlated with w/λ. Thus, $\partial Q_1{}^{RC}/\partial w < 0, \partial Q_1{}^{RC}/\partial \lambda > 0, \partial Q_1{}^{RC}/\partial \varphi > 0$.

The proof of Proposition 6 is provided in Appendix F.

Through the coordination of the freshness-keeping cost-sharing and revenue-sharing contract, we know that when φ/λ is certain, the optimal order quantity Q_1^{RC*} decreases with w/λ increase. Thus, the order quantity under contractual coordination is negatively related to the wholesale price w and positively related to the revenue-sharing ratio λ and freshness-keeping cost-sharing ratio φ. The supplier can attract the retailer to increase the order quantity by increasing the freshness-keeping cost-sharing and revenue-sharing ratios as well as reducing the wholesale price.

Proposition 7: When $\varphi = \lambda$, $w/\lambda = c$, then $\pi^{RC} = \pi^C$.

The proof of Proposition 7 is provided in Appendix G.

When the conditions $\varphi = \lambda$, $w/\lambda = c$ are satisfied, the total profits of the contract supply chain are equal to those of the centralized supply chain, thus achieving perfect coordination. Under the combination contract, we can adjust the ratio of the contract to attract retailer to make optimal decisions. When the ratio is adjusted to $\varphi = \lambda$ and $w/\lambda = $ c, the total expected profits of the supply chain will achieve the profits of the centralized supply chain, which achieves perfect coordination. The profits distribution between the retailer and supplier under a decentralized supply chain can be realized by setting the value of w, φ and λ, but only when the value is appropriate can the expected profits of the retailer and supplier increase at the same time.

VII. NUMERICAL EXAMPLES

To further validate the effectiveness of the model, we field research on the supply chain operation of the Jiajiayue Supermarket and its production base was conducted. Based on this, the relevant parameters were assigned with reference to existing literature. $E\theta(\tau) = 0.7, Ec(\tau) = 3, c_0 = 4, \theta_0 = 0.96, \tau^l = 0.15, \tau^u = 0.45, c = 6, s = 1.5, V = 22$.

Moreover, the demand for the three sales periods is set as $D_1 \sim N(170, 60^2), D_2 \sim N(110, 40^2), D_3 \sim N(40, 30^2)$, which can be obtained as $D_1 + D_2 \sim N(280, 72.11^2)$, $D_1 + D_2 + D_3 \sim N(320, 78.10^2)$. Freshness-keeping effort can slow down the decline of freshness, and the freshness in the discount period is lower than that in the normal period, but the difference is not significant. Hence, it is reasonable to take a higher demand for the discount period. Thus, the parameters are put into models to analyze the influence of freshness-keeping effort, valuation, and wholesale price on the pricing, order quantity, and profits. Finally, the corresponding conclusions are drawn.

Substituting these parameters into,, and, we explore the effect of freshness-keeping effort on optimal order quantity and selling prices. Comparative analysis of the difference in fresh-keeping effect with and without consideration of strategic consumers.

According to Fig. 2, the retailer makes a low-order quantity strategy under strategic consumers, which verifies the

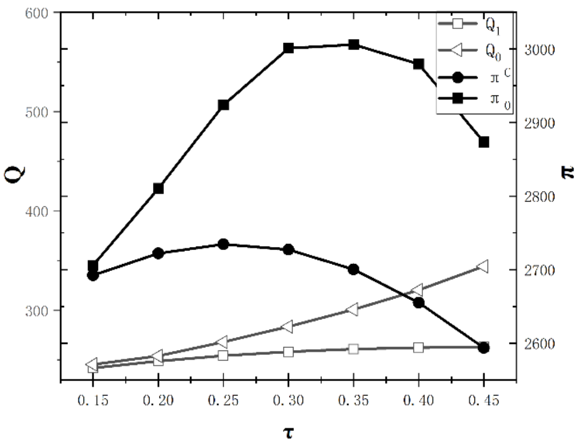

FIGURE 2. Impact of freshness-keeping effort on order quantity and profits.

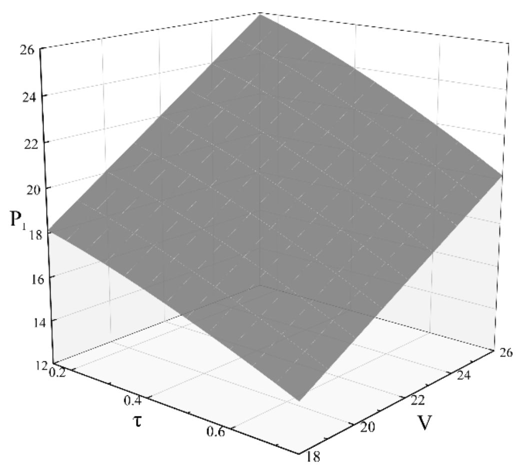

FIGURE 3. Impact of freshness-keeping effort and valuation on the normal price.

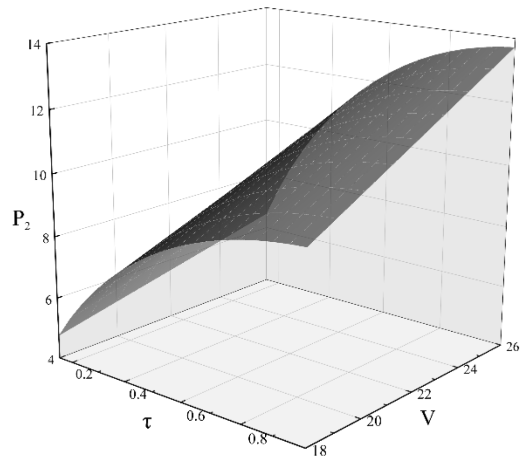

FIGURE 4. Impact of freshness-keeping effort and valuation on the discount price.

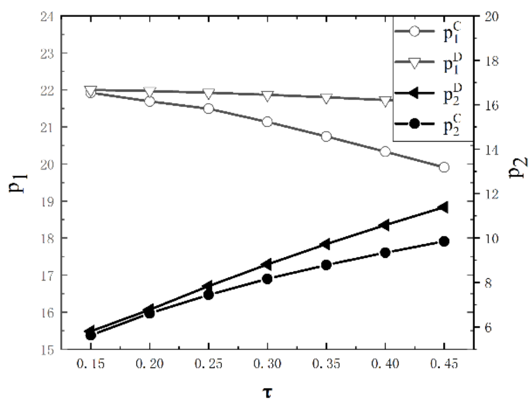

FIGURE 5. Price curves for both centralized and decentralized decision-making.

conclusions of the existing literature. Additionally, based on the influence curve of profits, the optimal freshness-keeping effort under strategic consumers is lower than without strategic consumers. Thus, the retailer chooses a lower freshness-keeping effort under strategic consumers, consistent with reality. Providing freshness-keeping effort can ease the loss of freshness. However, too much freshness-keeping effort not only leads to higher freshness-keeping cost but also makes strategic consumers wait to purchase more cost-effective products. Therefore, providing a lower freshness-keeping effort is the result of a combination of tradeoffs.

When the order quantity is certain, the effect of freshness-keeping effort and valuation on the optimal price can be explored, so let the $F_1(Q_1) = 0.8, H(Q_1) = 0.4, F(Q_1) = 0.2$, and the valuation interval is $[18, 26]$. We analyze the influence of freshness-keeping effort and valuation on prices during two selling periods, and obtain Fig. 3 and 4.

Based on Fig. 3 and 4, when the freshness-keeping effort is certain, the normal and discount prices increase with the valuation increase. When the valuation is certain, as freshness-keeping effort increases, the normal price decreases, and the discount price first increases and then decreases. A certain critical value exists. Therefore, supply chain members not only need to consider the freshness-keeping cost and consumer behavior, but also need to consider the price mechanism of the two sales periods to make the optimal decision when choosing the freshness-keeping effort.

Strategic consumers favor delayed purchases if the freshness in the discount and clearance periods are still good. At the same time, valuation limits pricing, the higher the valuation, the higher the price. Therefore, it is necessary to consider the valuation, freshness-keeping effort, and consumer strategic behavior to make the optimal freshness-keeping decision and reduce the influence of strategic consumers on supply chain profits.

Fig. 5 illustrates the validation of Proposition 5. The discount and normal prices follow the same trend, respectively, in both centralized and decentralized supply chain.

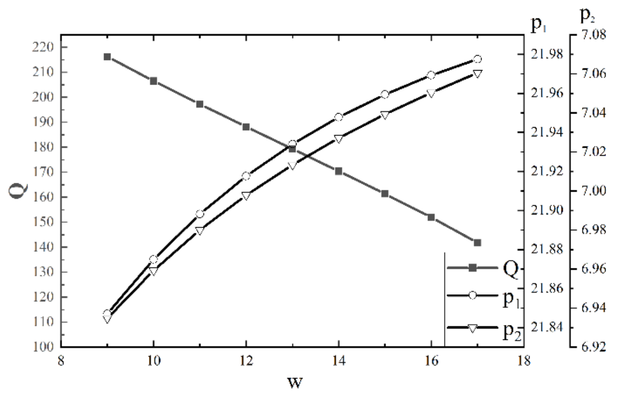

FIGURE 6. Impact of wholesale price on order quantities and normal and discount price.

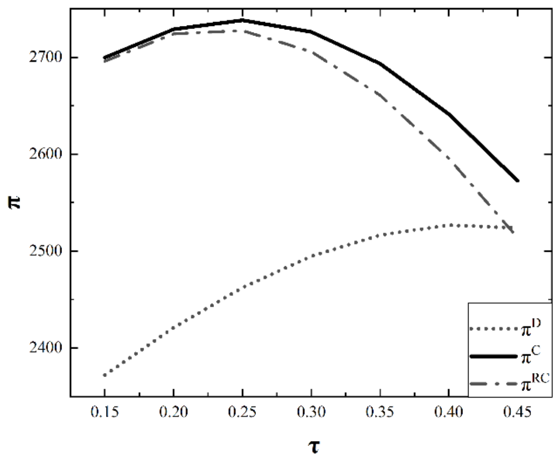

FIGURE 7. Impact of freshness-keeping effort on centralization and decentralization of supply chain profits.

According to Fig. 6, in the decentralized decision-making supply chain, the retailer's order quantity is negatively correlated with the wholesale price provided by the supplier. In contrast, the prices in normal and discount periods are positively correlated with the wholesale price. This verifies that the wholesale price affects optimal decision-making, and the supplier can motivate retailer to order more fresh products by appropriately reducing the wholesale price.

As shown in Fig. 7, the expected profits of the decentralized supply chain are lower than that of the centralized when $w = 5, \varphi = 0.55, \lambda = 0.55$. The difference between the two profits tends to decrease with freshness-keeping effort increase. At the same time, we can also see that the effect of the contract is better when the freshness-keeping effort is low, which is consistent with the low freshness-keeping effort strategy mentioned above. However, according to Fig. 8, supplier profits are positively correlated with freshness-keeping effort, and retailer profits show a decreasing trend when freshness-keeping effort exceeds a certain value. At this time, the retailer's motivation for providing freshness-keeping effort is insufficient, so it is necessary to take an appropriate contract to coordinate, which leads to an increase in the total expected profits of the supply chain.

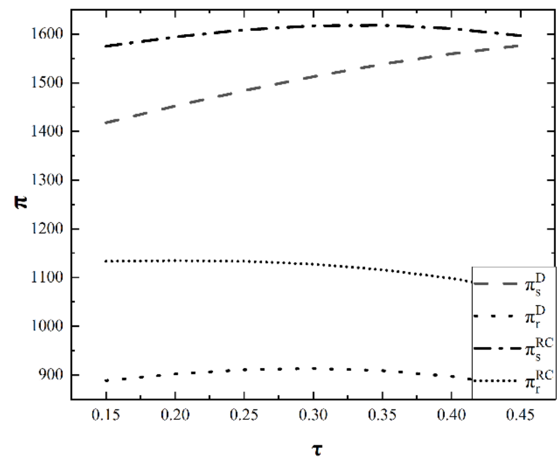

FIGURE 8. Impact of freshness-keeping effort on retailers and suppliers of supply chain profits.

Additionally, according to Fig. 7 and 8, the expected profits of the supply chain under the freshness-keeping cost-sharing and revenue-sharing contract are better than that of the decentralized supply chain without contractual coordination. The expected profits of the supplier and retailer both increase under contractual coordination, which verifies the contract's optimization effect. So, the sharing among supply chain members is achieved, and it can motivate both supplier and retailer to keep this contract.

VIII. CONCLUSION

With the development of the market economy, the demand for fresh agricultural products has gradually increased, and the demand for freshness and quality is also increasing. Although we can incentivize consumption in many ways, such as freshness-keeping, discounting, and finishing. The level of freshness-keeping is limited by cost. Hence, more incentives for members to undertake freshness-keeping effort are needed.

Therefore, we focused on the cooperative freshness-keeping of the fresh products supply chain as well as the interaction with the actual consumption behavior of consumers. Based on this, supply chain coordination strategies are explored to improve overall efficiency, which is significant for improving operational performance and quality of life. We established a rational decision-making model and analyzed the influence mechanism of freshness-keeping effort and valuation on the dynamic decision-making of the products supply chain.

1) The optimal freshness-keeping effort, order quantity, and expected profits based on strategic consumers are all reduced. The low order quantity strategy verifies the existing research, but the low freshness-keeping effort strategy does not appear in the previous research. Therefore, retailers can adopt low freshness-keeping effort and low order quantity strategy to incentivize consumers to buy immediately.

2) In previous studies, the relationship between price and freshness-keeping effort is usually linear and positive. But it is not so monotonous in our study. The normal price is negative with freshness-keeping effort. The relationship between freshness-keeping effort and the discount price is positive when freshness effort is low and negative when freshness effort exceeds a critical value.
3) The relationship between freshness-keeping effort and order quantity is negatively correlated under certain conditions, which is slightly different from the existing research.
4) The effect of the contract is better when the freshness-keeping effort is low, which is consistent with the low freshness-keeping effort strategy mentioned above.
5) Freshness-keeping cost-sharing and revenue-sharing contract can optimize the dynamic decision-making model and improve the expected profits of decentralized supply chain. As well as realize perfect coordination of the fresh agricultural products supply chain.

The low freshness-keeping effort strategy is not reflected in other relevant literature because this strategy can only be obtained by taking into account the dynamic pricing process of the fresh agricultural supply chain with strategic consumers, which is closer to reality than the static or without strategic consumers' model.

The conclusions of this study can help supply chain members better understand the influence of strategic behavior on dynamic decision-making and enrich the research related to dynamic pricing. This can also inspire management practices. First, according to the dynamic decision-making model, better planning can be achieved by adjusting pricing, order quantity, and freshness-keeping effort. Second, the numerical simulation proves that the freshness-keeping cost-sharing and revenue-sharing contract can improve the profits of the decentralized supply chain, which provides a new idea for dynamic management. Additionally, a coordination mechanism can be used to improve profits.

The following is a discussion of the shortcomings of this study and further research in the future. In this study, we examined the influence of homogeneous strategic consumers' strategic behavior on optimal decision-making in the case of complete rationality. Future research can consider the change in optimal decision-making in cases of incomplete rationality or heterogeneous consumers. Furthermore, this study only considered retailer freshness-keeping. Further research could investigate the influence of freshness-keeping effort on supply chain decisions and profits when suppliers preserve fresh agricultural products. The optimal decision-making of the entire supply chain system when adding a third-party logistics service provider also deserves further study.

ACKNOWLEDGMENT

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APPENDIX A

Proof of Proposition 1: (1)The first and second order derivatives of the supply chain profits function concerning the order quantity are:

$$\begin{aligned}\frac{\partial E[\pi^C]}{\partial Q_1} &= [p_2 - p_1 - c(\tau)]\,F_1(Q_1^C) - (p_2 - s)H(Q_1^C)\\ &\quad - sF_1(Q_1^C) + p_1 - c - c(\tau),\\ \frac{\partial^2 E[\pi^C]}{\partial {Q_1}^2} &= [p_2 - p_1 - c(\tau)]f_1(Q_1^C) - (p_2 - s)h(Q_1^C)\\ &\quad - sf_1(Q_1^C) < 0. \end{aligned} \tag{15}$$

The expected profits function is a strictly concave function of the order quantity. There exists a unique optimal order quantity to maximize the expected profits because $p_1 > c + c(\tau)$, and the first order derivative of the expected profits function of is equal to 0. That is:

$$\begin{aligned}&[p_2 - p_1 - c(\tau)]\,F_1(Q_1^{C^*}) - (p_2 - s)H(Q_1^{C^*})\\ &\quad - sF_1(Q_1^{C^*}) + p_1 - c - c(\tau) = 0. \end{aligned} \tag{16}$$

(2) According to the rational expectations equilibrium, the two-period price expression can be obtained as ${p_1}^{C^*} = V_1 - [V_2 - p_2]F_1(Q_1^{C^*})$, ${p_2}^{C^*} = V_2 - [V_3 - s]H(Q_1^{C^*})/F_1(Q_1^{C^*})$, substituting the freshness function $V_i = \theta_i(\tau)V$, $i = 1, 2, 3$ gives ${p_1}^{C^*} = V - [\theta(\tau)V - p_2]F_1(Q_1^{C^*})$, ${p_2}^{C^*} = \theta(\tau)V - [\theta^2(\tau)V - s]H(Q_1^{C^*})/F_1(Q_1^{C^*})$, which can be further obtained using and, Finally, the sales price of the two periods in the formula and simplifying the organization can be obtained using.

(3) When the order quantity is exogenous,

$$\begin{aligned}&\frac{\partial E[\pi^C]}{\partial \tau}\\ &= [{p_2}'(\tau) - {p_1}'(\tau) - c'(\tau)]\int_0^{Q_1} F_1(x_1)dx_1\\ &\quad - {p_2}'(\tau)\int_0^{Q_1} H(m)dm + [{p_1}'(\tau) - c'(\tau)]Q_1\\ &= [\theta'(\tau)V + 2\theta(\tau)\theta'(\tau)VH(Q_1)(1 - 1/F_1(Q_1)) - c'(\tau)]\\ &\quad \times \int_0^{Q_1} F_1(x_1)dx_1 + [-2\theta(\tau)\theta'(\tau)VH(Q_1) - c'(\tau)]Q_1\\ &\quad - \theta'(\tau)[1 - 2\theta(\tau)H(Q_1)/F_1(Q_1)]\int_0^{Q_1} H(m)dm\\ &\frac{\partial^2 E[\pi^C]}{\partial \tau^2}\\ &= [\theta''(\tau)V + 2aVH(Q_1)(1 - 1/F_1(Q_1)) - c''(\tau)]\\ &\quad \times \int_0^{Q_1} F_1(x_1)dx_1 - [-2aVH(Q_1)/F_1(Q_1) - c''(\tau)]Q_1\\ &\quad - [\theta''(\tau)V - 2aVH(Q_1)/F_1(Q_1)]\int_0^{Q_1} H(m)dm\\ &= \theta''(\tau)V[\int_0^{Q_1} F_1(x_1)dx_1 - \int_0^{Q_1} H(m)dm] - 2aVH(Q_1)\\ &\quad [(Q_1 - \int_0^{Q_1} F_1(x_1)dx_1) + (\int_0^{Q_1} F_1(x_1)dx_1 + \int_0^{Q_1} \end{aligned}$$

$$H(m)dm)/F_1(Q_1)] - c''(\tau)[Q_1 + \int_0^{Q_1} F_1(x_1)dx_1]$$

$$\begin{aligned}\frac{\partial^2 E[\pi^C]}{\partial\tau^2} &= [\theta''(\tau)V + 2aVH(Q_1)(1-1/F_1(Q_1)) - c''(\tau)] \\ &\times \int_0^{Q_1} F_1(x_1)dx_1 - [-2aVH(Q_1)/F_1(Q_1) - c''(\tau)]Q_1 \\ &- [\theta''(\tau)V - 2aVH(Q_1)/F_1(Q_1)] \int_0^{Q_1} H(m)dm \\ &= \theta''(\tau)V[\int_0^{Q_1} F_1(x_1)dx_1 - \int_0^{Q_1} H(m)dm] - 2aVH(Q_1) \\ &\times [(Q_1 - \int_0^{Q_1} F_1(x_1)dx_1) + (\int_0^{Q_1} F_1(x_1)dx_1 + \int_0^{Q_1} \\ &H(m)dm)/F_1(Q_1)] - c''(\tau)[Q_1 + \int_0^{Q_1} F_1(x_1)dx_1]\end{aligned}$$

where $a = [\theta'(\tau)]^2 + \theta(\tau)\theta''(\tau)$.

Because $c''(\tau) > 0, \theta''(\tau) < 0$, $Q_1 - \int_0^{Q_1} F_1(x_1)dx_1 > 0$, $\int_0^{Q_1} F_1(x_1)dx_1 - \int_0^{Q_1} H(m)dm > 0$,

$$\begin{aligned}a &= [\theta'(\tau)]^2 + \theta(\tau)\theta''(\tau) \\ &= {\theta_0}^2[E\theta(\tau)]^2\tau^{2E\theta(\tau)-2} + {\theta_0}^2[E\theta(\tau)(E\theta(\tau)-1)]\tau^{2E\theta(\tau)-2} \\ &= {\theta_0}^2\tau^{2E\theta(\tau)-2}E\theta(\tau)(2E\theta(\tau)-1),\end{aligned}$$

When $E\theta(\tau) \in (0.5, 1)$, $a > 0$, when $E\theta(\tau) \in (0, 0.5)$, $a < 0$, for $E[\pi^C]$ to be strictly concave with τ, this study only discusses the case of $a > 0$, i.e. $E\theta(\tau) \in (0.5, 1)$.
So $\partial^2 E[\pi^C]/\partial\tau^2 < 0$.

When $\partial E[\pi^C]/\partial\tau = 0$, $\tau = \tau^0$.

If $\tau < \tau^0$, $\partial E[\pi^C]/\partial\tau > 0$. If $\tau > \tau^0$, $\partial E[\pi^C]/\partial\tau < 0$.

Because $\tau \in [\tau^l, \tau^u]$,

If $\tau^0 \leqslant \tau^l$, within $[\tau^l, \tau^u]$, $\partial E[\pi^C]/\partial\tau < 0$, then $\tau^{C^*} = \tau^l$,

If $\tau^l < \tau^0 < \tau^u$, within $[\tau^l, \tau^u]$, when $\tau^l < \tau < \tau^0$, $\partial E[\pi^C]/\partial\tau > 0$, when $\tau^0 < \tau < \tau^u$, $\partial E[\pi^C]/\partial\tau < 0$, then $\tau^{C^*} = \tau^0$,

If $\tau^0 \geqslant \tau^u$, within $[\tau^l, \tau^u]$, $\partial E[\pi^C]/\partial\tau > 0$ then $\tau^{C^*} = \tau^u$. Q.E.D.

APPENDIX B

Proof of Corollary 1: Substituting ${p_1}^{0^*}$, ${p_2}^{0^*}$ into (16) shows that

$$\begin{aligned}&[\theta(\tau)V - V - c(\tau)]F_1(Q_1^{0^*}) - [\theta(\tau)V - s]H(Q_1^{0^*}) \\ &\quad -sF(Q_1^{0^*}) + V - c - c(\tau) = 0.\end{aligned} \tag{17}$$

Comparing (9), (17), and organizing (9) we have

$$\begin{aligned}&[\theta(\tau)V - V - c(\tau)]F_1(Q_1^{C^*}) - [\theta(\tau)V - s]H(Q_1^{C^*}) \\ &\quad -sF(Q_1^{C^*}) + V - c - c(\tau) + A = 0.\end{aligned}$$

where

$$A = [\theta^2(\tau)V - s]H(Q_1^{C^*})[-2 + F_1(Q_1^{C^*}) + H(Q_1^{C^*})/F_1(Q_1^{C^*})].$$

For all $Q_1 > 0$ exists $0 < F(Q_1) < H(Q_1) < F_1(Q_1) < 1$, so $H(Q_1)/F_1(Q_1) < 1$, we know $A < 0$. In that way:

$$\begin{aligned}&[\theta(\tau)V - V - c(\tau)]F_1(Q_1^{0^*}) - [\theta(\tau)V - s]H(Q_1^{0^*}) - sF(Q_1^{0^*}) \\ &< [\theta(\tau)V - V - c(\tau)]F_1(Q_1^{C^*}) - [\theta(\tau)V - s]H(Q_1^{C^*}) \\ &\quad - sF(Q_1^{C^*}).\end{aligned}$$

The change of sign shows that $Q_1^{0^*} > Q_1^{C^*}$. Q.E.D.

APPENDIX C

Proof of Proposition 3: (1)The derivative of ${p_1}^D$ with respect to the order quantity ${Q_1}^D$ is:

$$\frac{\partial {p_1}^D}{\partial {Q_1}^D} = -[\theta^2(\tau)V - s]h({Q_1}^D) < 0.$$

The correlation between ${p_2}^D$ and ${Q_1}^D$ is analyzed using the implicit function differentiation method, which is simplified and organized according to under decentralized decision-making to get, as shown in the equation at the bottom of the page.

Associated with ${p_1}^D = V - [\theta(\tau)V - p_2]F_1(Q_1^D)$, let

$$\begin{aligned}T({Q_1}^D, {p_2}^D) &= V[1 - F_1({Q_1}^D)] + [{p_2}^D - c(\tau)]F_1({Q_1}^D) \\ &\quad - [\theta(\tau)V - {p_2}^D]F_1({Q_1}^D)[1 - F_1({Q_1}^D)] \\ &\quad - ({p_2}^D - s)H({Q_1}^D) - sF({Q_1}^D) - w - c(\tau).\end{aligned}$$

Find the first order derivative of $T({p_2}^D, {Q_1}^D)$ with respect to ${p_2}^D$ and ${Q_1}^D$ respectively

$$\begin{aligned}&T'_{{p_2}^D}({Q_1}^D, {p_2}^D) \\ &= F_1({Q_1}^D)[1 - F_1\left({Q_1}^D\right)] + F_1\left({Q_1}^D\right) - H\left({Q_1}^D\right) > 0, \\ &T'_{{Q_1}^D}({Q_1}^D, {p_2}^D) \\ &= f_1({Q_1}^D)B - ({p_2}^D - s)h({Q_1}^D) - sf({Q_1}^D),\end{aligned}$$

where $B = -V - [\theta(\tau)V - {p_2}^D][1 - 2F_1({Q_1}^D)] + [{p_2}^D - c(\tau)]$.

Substituting ${p_2}^D = \theta(\tau)V - [\theta^2(\tau)V - s]H(Q_1^D)/F_1(Q_1^D)$ into B, and then simplifying and organizing it shows that

$$\begin{aligned}B &= -2[\theta^2(\tau)V - s]H({Q_1}^D)[1 - F_1({Q_1}^D)]/F_1({Q_1}^D) \\ &\quad - V[1 - \theta(\tau)] - c(\tau) < 0,\end{aligned}$$

because $f(Q_1^D) > 0, -({p_2}^D - s)h(Q_1^D) - sf(Q_1^D) < 0$, therefore $T'_{Q_1^D}({Q_1}^D, {p_2}^D) < 0$. So we can get:

$$\frac{\partial {p_2}^D}{\partial {Q_1}^D} = -\frac{T'_{Q_1^D}({Q_1}^D, {p_2}^D)}{T'_{{p_2}^D}({Q_1}^D, {p_2}^D)} > 0.$$

$${p_1}^D = \frac{-[{p_2}^D - c(\tau)]F_1({Q_1}^D) + ({p_2}^D - s)H({Q_1}^D) + sF({Q_1}^D) + w + c(\tau)}{1 - F_1({Q_1}^D)}.$$

Thus, when V and τ are certain, the price is negatively related to order quantity during the normal period, and positively related to order quantity during the discount period.

(2) Regarding and, the derivative of the valuation V, respectively, shows that

$$\frac{\partial p_1{}^D}{\partial V} = 1-\theta^2(\tau)H(Q_1{}^D) > 0\,,$$
$$\frac{\partial p_2{}^D}{\partial V} = \theta(\tau)[1-\theta(\tau)H(Q_1{}^D)/F(Q_1{}^D)] > 0.$$

Therefore, when Q_1 and τ are certain, the sales price increases in both periods as the valuation V increases. Q.E.D.

APPENDIX D

Proof of Proposition 4: (1) The derivative of normal price with respect to the freshness-keeping effort is:

$$\frac{\partial p_1{}^D}{\partial \tau} = -2\theta(\tau)\theta'(\tau)VH(Q_1{}^D) < 0.$$

(2) The derivative of the normal discount price with respect to the freshness-keeping effort is:

$$\frac{\partial p_2{}^D}{\partial \tau} = \theta'(\tau)V\left[1-2\theta(\tau)H(Q_1{}^D)/F_1(Q_1{}^D)\right].$$

When $1-2\theta(\tau)H(Q_1{}^D)/F_1(Q_1{}^D) = 0$, $\partial p_2{}^D/\partial\tau = 0$, this moment $\tau = [F_1(Q_1{}^D)/2\theta_0 H(Q_1{}^D)]^{1/E\theta(\tau)}$.

When $\tau < [F_1(Q_1{}^D)/2\theta_0 H(Q_1{}^D)]^{1/E\theta(\tau)}$, $\theta(\tau) < F_1(Q_1{}^D)/2H(Q_1{}^D)$, $\partial p_2{}^D/\partial\tau > 0$;

when $\tau > [F_1(Q_1{}^D)/2\theta_0 H(Q_1{}^D)]^{1/E\theta(\tau)}$, $\theta(\tau) > F_1(Q_1{}^D)/2H(Q_1{}^D)$, $\partial p_2{}^D/\partial\tau < 0$. Prices increased and then decreased during the discount periodas freshness-keeping effort increased.

(3) ① When $\theta(\tau) > F_1(Q_1{}^D)/2H(Q_1{}^D)$, with the freshness-keeping effort increases, the cost of freshness-keeping increases, whereas the prices decrease in both periods. Therefore $c(\tau) < \overline{c(\tau)}$, $p_1{}^D > \overline{p_1{}^D}$, $p_2{}^D > \overline{p_2{}^D}$, might also result in $\overline{c(\tau)} = c(\tau)+\Delta c(\tau)$, $\overline{p_1{}^D} = p_1{}^D-\Delta p_1{}^D$, $\overline{p_2{}^D} = p_2{}^D-\Delta p_2{}^D$,where $\Delta p_i{}^D > 0$. The following equation can be obtained from (16):

$$[\overline{p_2{}^D}-\overline{p_1{}^D}-\overline{c(\tau)}]F_1(\overline{Q_1{}^D})-(\overline{p_2{}^D}-s)H(\overline{Q_1{}^D})$$
$$-sF(\overline{Q_1{}^D})+\overline{p_1{}^D}-c-\overline{c(\tau)} = 0.$$

Simplification and organization show that:

$$[p_2{}^D-p_1{}^D-c(\tau)]F_1(\overline{Q_1{}^D})-\left(p_2{}^D-s\right)H(\overline{Q_1{}^D})$$
$$-sF(\overline{Q_1{}^D})+p_1{}^D-c-c(\tau)+D = 0,$$

where

$$D = -\Delta p_2{}^D[F_1(\overline{Q_1{}^D})-H(\overline{Q_1{}^D})]-\Delta p_1{}^D[1-F_1(\overline{Q_1{}^D})]$$
$$-\Delta c(\tau)[1+F_1(\overline{Q_1{}^D})] < 0.$$

So, we can get the following:

$$[p_2{}^D-p_1{}^D-c(\tau)]F_1(\overline{Q_1{}^D})-\left(p_2{}^D-s\right)H(\overline{Q_1{}^D})-sF(\overline{Q_1{}^D})$$
$$> [p_2{}^D-p_1{}^D-c(\tau)]F_1(Q_1{}^D)-\left(p_2{}^D-s\right)H(Q_1{}^D)$$
$$-sF(Q_1{}^D).$$

Converting the symbols and gets $Q_1^D > \overline{Q_1^D}$. Thus, freshness-keeping effort is negatively related to order quantity when $\theta(\tau) > F_1(Q_1{}^D)/2H(Q_1{}^D)$.

② When $\theta(\tau) < F_1(Q_1{}^D)/2H(Q_1{}^D)$, with freshness-keeping effort increases, both the freshness-keeping cost and freshness increase so that it can be seen that $c(\tau) < \overline{c(\tau)}$, $\theta(\tau) < \overline{\theta(\tau)}$, might also result in $\overline{c(\tau)} = c(\tau)+\Delta c(\tau)$, $\overline{\theta(\tau)} = \theta(\tau)+\Delta\theta(\tau)$. According to and simplify and organize to obtain the following equation:

$$[\theta(\tau)V-V-c(\tau)]F_1(\overline{Q_1{}^D})-[\theta(\tau)V-s]H(\overline{Q_1{}^D})-sF(\overline{Q_1{}^D})$$
$$+[\theta^2(\tau)V-s]H(\overline{Q_1{}^D})E_1+V-c-c(\tau)+E_2 = 0,$$

where $E_1 = -2+F_1(\overline{Q_1{}^D})+H(\overline{Q_1{}^D})/F_1(\overline{Q_1{}^D}) < 0$,

$$\begin{aligned}E_2 &= \Delta\theta(\tau)V[F_1(\overline{Q_1{}^D})-H(\overline{Q_1{}^D})]+\Delta\theta^2(\tau)VH(\overline{Q_1{}^D})E_1-E_3\\ &< \overline{\theta(\tau)}V[F_1(\overline{Q_1{}^D})-H(\overline{Q_1{}^D})]+\overline{\theta^2(\tau)}VH(\overline{Q_1{}^D})E_1-E_3\\ &< V[F_1(\overline{Q_1{}^D})-H(\overline{Q_1{}^D})]F_1(\overline{Q_1{}^D})/2H(\overline{Q_1{}^D})\\ &\quad +VE_1F_1{}^2(\overline{Q_1{}^D})/4H(\overline{Q_1{}^D})-E_3\\ &= \tfrac{1}{4}F_1(\overline{Q_1{}^D})V\left[-1+F_1{}^2(\overline{Q_1{}^D})/H(\overline{Q_1{}^D})\right]-E_3,\end{aligned}$$
$$E_3 = \Delta c(\tau)[1+F_1(\overline{Q_1{}^D})].$$

When $F_1{}^2(\overline{Q_1{}^D}) < H(\overline{Q_1{}^D})$, then $E_2 < 0$, that is $Q_1^D > \overline{Q_1{}^D}$, thus, when $\theta(\tau) > F_1(Q_1{}^D)/2H(Q_1{}^D)$ and $F_1{}^2(\overline{Q_1{}^D}) < H(\overline{Q_1{}^D})$ the freshness-keeping effort is negatively correlated with the order quantity.

In summary, when the condition $F_1{}^2(\overline{Q_1{}^D}) < H(\overline{Q_1{}^D})$ is satisfied, the freshness-keeping effort is negatively related to optimal order quantity. Q.E.D.

APPENDIX E

Proof of Proposition 5: (1) Comparing,, and organizing we obtain

$$[\theta(\tau)V-V-c(\tau)]F_1(Q_1^{C^*})-[\theta(\tau)V-s]H(Q_1^{C^*})$$
$$+[\theta^2(\tau)V-s]H(Q_1^{C^*})[-2+F_1(Q_1^{C^*})+H(Q_1^{C^*})/F_1(Q_1^{C^*})]$$
$$-sF(Q_1^{C^*})+V-c-c(\tau) = 0.$$

Organizing process as above, and because of $w > c$, the sign can be changed after $Q_1^{D^*} < Q_1^{C^*}$.

(2) Because $Q_1^{D^*} < Q_1^{C^*}$ can be obtained from $H(Q_1^{D^*}) < H(Q_1^{C^*})$, according to the normal price expressions and can be analyzed by comparing $p_1{}^{D^*}-p_1{}^{C^*} = -[\theta^2(\tau)V-s][H(Q_1^{D^*})-H(Q_1^{C^*})] > 0$, so $p_1{}^{D^*} > p_1{}^{C^*}$.

$$\begin{aligned}&p_2{}^{D^*}-p_2{}^{C^*}\\ &= -(V-p_1{}^{D^*})/F_1(Q_1^{D^*})+(V-p_1{}^{C^*})/F_1(Q_1^{C^*})\\ &= [-(V-p_1{}^{D^*})F_1(Q_1^{C^*})+(V-p_1{}^{C^*})F_1(Q_1^{D^*})]/F_1(Q_1^{D^*})\\ &\quad\times F_1(Q_1^{C^*})\\ &> [-(V-p_1{}^{C^*})F_1(Q_1^{D^*})+(V-p_1{}^{C^*})F_1(Q_1^{D^*})]/F_1(Q_1^{D^*})\\ &\quad\times F_1(Q_1^{C^*})\\ &= 0,\end{aligned}$$

so, $p_2{}^{D^*} > p_2{}^{C^*}$.

(3) Let $\Delta_1 = E[\pi^C] - E[\pi^D]$, so

$$\begin{aligned}\Delta_1 = {} & [p_2{}^C - p_1{}^C - c(\tau)] \int_0^{Q_1{}^C} F_1(x_1)dx_1 - (p_2{}^C - s) \int_0^{Q_1{}^C} H(m)dm - s\int_0^{Q_1{}^C} F(x)dx + [p_1{}^C - c - c(\tau)]Q_1{}^C \\ & + s\int_0^{Q_1{}^D} F(x)dx + [p_1{}^D - p_2{}^D + c(\tau)] \int_0^{Q_1{}^D} F_1(x_1)dx_1 \\ & + (p_2{}^D - s) \int_0^{Q_1{}^D} H(m)dm - [p_1{}^D - w - c(\tau)]Q_1{}^D.\end{aligned}$$

Because $Q_1^{D^*} < Q_1^{C^*}, p_1{}^{D^*} > p_1{}^{C^*}, p_2{}^{D^*} > p_2{}^{C^*}$, then

$$\begin{aligned}\Delta_1 > {} & [p_2{}^C - p_1{}^C - c(\tau)] \int_0^{Q_1{}^D} F_1(x_1)dx_1 - (p_2{}^C - s) \int_0^{Q_1{}^D} H(m)dm - s\int_0^{Q_1{}^D} F(x)dx + [p_1{}^C - c - c(\tau)]Q_1{}^D \\ & + s\int_0^{Q_1{}^D} F(x)dx + s\int_0^{Q_1{}^D} F(x)dx + [p_1{}^C - p_2{}^C \\ & + c(\tau)] \int_0^{Q_1{}^D} F_1(x_1)dx_1 + (p_2{}^C - s) \int_0^{Q_1{}^D} H(m)dm \\ & - [p_1{}^C - w - c(\tau)]Q_1{}^D \\ = {} & (w - c)Q_1{}^D > 0.\end{aligned}$$

So $\Delta_1 = E[\pi^C] - E[\pi^D] > 0$. In summary, the profits of the centralized supply chain are always higher than that of decentralized supply chain. Q.E.D.

APPENDIX F

Proof of Proposition 6: When φ/λ is certain, as w/λ increases, we make $\overline{w}/\lambda = w/\lambda + \Delta w/\lambda$, and we can obtain the following equation:

$$\begin{aligned} & [\theta(\tau)V - V - \frac{\varphi}{\lambda}c(\tau)]F_1(\overline{Q_1^{RC}}) - [\theta(\tau)V - s]H(\overline{Q_1^{RC}}) \\ & - sF(\overline{Q_1^{RC}}) + [\theta^2(\tau)V - s]H(\overline{Q_1^{RC}})[-2 + F_1(\overline{Q_1^{RC}}) \\ & + H(\overline{Q_1^{RC}})/F_1(\overline{Q_1^{RC}})] + V - \frac{w}{\lambda} - \frac{\varphi}{\lambda}c(\tau) - \frac{\Delta w}{\lambda} = 0.\end{aligned}$$

The analytical process refers to Corollary 1, Comparison with, we can see that $Q_1^{RC} > \overline{Q_1^{RC}}$, so as w/λ increases, Q_1^{RC} decreases. Q.E.D.

APPENDIX G

Proof of Proposition 7. When $\varphi = \lambda$, $w/\lambda = c$, we can obtain the retailer's expected profits:

$$\begin{aligned}E[\pi_r{}^{RC}] = {} & \lambda\{[p_2{}^{RC} - p_1{}^{RC} - c(\tau)] \int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 \\ & - s\int_0^{Q_1{}^{RC}} F(x)dx - \left(p_2{}^{RC} - s\right) \int_0^{Q_1{}^{RC}} H(m)dm \\ & + [p_1{}^{RC} - c - c(\tau)]Q_1{}^{RC}\}.\end{aligned}$$

The supplier expects the profits to be:

$$\begin{aligned}E[\pi_s{}^{RC}] = {} & (1-\lambda)\{[p_2{}^{RC} - p_1{}^{RC} - c(\tau)] \int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 \\ & - s\int_0^{Q_1{}^{RC}} F(x)dx - \left(p_2{}^{RC} - s\right) \int_0^{Q_1{}^{RC}} H(m)dm \\ & + [p_1{}^{RC} - c - c(\tau)]Q_1{}^{RC}\}.\end{aligned}$$

The total profits under contractual coordination are:

$$\begin{aligned}E[\pi^{RC}] = {} & [p_2{}^{RC} - p_1{}^{RC} - c(\tau)] \int_0^{Q_1{}^{RC}} F_1(x_1)dx_1 \\ & - \left(p_2{}^{RC} - s\right) \int_0^{Q_1{}^{RC}} H(m)dm - s\int_0^{Q_1{}^{RC}} F(x)dx \\ & + [p_1{}^{RC} - c - c(\tau)]Q_1{}^{RC}.\end{aligned}$$

And $p_1{}^{RC} = V - [\theta^2(\tau)V - s]H(Q_1^{RC})$, $p_2{}^{RC} = \theta(\tau)V - [\theta^2(\tau)V - s]H(Q_1^{RC})/F_1(Q_1^{RC})$, so Q_1^{RC} is determined by the following equation.

$$\begin{aligned} & [\theta(\tau)V - V - c(\tau)]F_1(Q_1^{\mathrm{RC}}) - [\theta(\tau)V - s]H(Q_1^{\mathrm{RC}}) \\ & - sF(Q_1^{\mathrm{RC}}) + [\theta^2(\tau)V - s]H(Q_1^{\mathrm{RC}})[-2 + F_1(Q_1^{\mathrm{RC}}) \\ & + H(Q_1^{\mathrm{RC}})/F_1(Q_1^{\mathrm{RC}})] + V - c - c(\tau) = 0.\end{aligned}$$

where $Q_1^{RC} = Q_1^C$, so $p_1{}^{RC} = p_1{}^C$, $p_2{}^{RC} = p_2{}^C$. In summary, when $\varphi = \lambda$, $w/\lambda = c$ are satisfied, the supply chain order quantity, two-period price, and total profits under contractual coordination are equal to centralized decision-making, and perfect coordination is achieved. Q.E.D.

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