

Dynamic Decision-making and Coordination Optimization of Fresh Produce Supply Chain

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Abstract. As an important part of modern agriculture, fresh agricultural products are closely related to the lives of residents and are an important cornerstone of national economic development. In recent years, consumer demand for high-quality, high-freshness products has grown, making supply chain management more difficult. In order to maintain competitiveness in the market, supply chain members need to dynamically adjust their freshness efforts and adopt coordination mechanisms to optimize benefits. Based on differential game theory, this paper analyzes the behavior and equilibrium strategy of supply chain under centralized decision-making, decentralized decision-making and coordination mechanism, studies the impact of key parameters such as consumer freshness preference, the degree of influence of freshness effort on freshness on decision-making, as well as the relationship between the dynamic change of supply chain members' profits in different scenarios, and conducts numerical simulation using MATLAB. The results show that consumer freshness preference positively affects product freshness and preservation effort, while the cost coefficient of preservation effort and the price elasticity coefficient have a negative effect. In the centralized decision-making model, steady-state product freshness, preservation effort and profit are higher than in the decentralized decision-making model; the cost-sharing contract can significantly improve the overall efficiency of the supply chain, but the retailer's profit is slightly lower than in the decentralized decision-making model.

Keywords: Fresh Produce Supply Chain; Differential Game; Coordination Mechanisms.

1. Introduction

As an important food category in daily life, fresh produce has gradually shifted its market focus from price to high quality and freshness as a result of the continued rise in residents' incomes and consumption levels. Freshness has become the key criterion for consumers to judge quality, prompting retailers to give preference to suppliers with high freshness. To meet consumer demand for freshness, suppliers need to invest heavily in freshness, for example by improving cold chain technology, optimizing storage conditions or speeding up distribution. While these measures can significantly improve freshness, they come at a higher cost and reduce suppliers' profit margins. Therefore, in the highly competitive fresh produce market, key supply chain management issues have become how to balance the relationship between freshness costs and revenues while satisfying consumer demand, how to formulate optimal dynamic pricing and decision strategies, and how to design appropriate contracts to coordinate the interests of all parties in the supply chain.

As for the research on fresh produce supply chain decision making, Wang et al [1] established an optimization model of fresh produce supply chain considering the costs and benefits of cold chain, and determined the optimal input level and optimal pricing of cold chain construction and promotion; Chen et al [2] constructed a master-slave game model in the fresh produce supply chain, and compared and analyzed the optimal pricing, distribution period, and preservation effort level of the two types of resale methods of paying service fee and deemed buyout; Zhao et al [3] considered the wastage improvement effect and the premium effect of the smart agriculture technology, and constructed the game model of the second-tier fresh produce supply chain to study the impact of different power structures on the smart agriculture technology supply chain, and investigated the impact of different power structures on the pricing and coordination of the two types of resale methods of paying service fee and deemed buyout. Power structures on the pricing and coordination of the fresh produce supply chain considering smart agriculture technology. Ma et al [4] considered how

fresh produce suppliers should provide optimal freshness input levels and carbon reduction strategies when consumer demand is affected by price, product freshness and product environmental friendliness, and pointed out that when a supplier adopts carbon reduction technology, the supplier will provide a higher level of freshness input regardless of parameter variations. Luo et al [5] proposed a goodwill-based traceability-based dynamic pricing and coordination differential game model for optimizing the operational efficiency and profitability of the supply chain, aiming to solve the current pricing and coordination problems in fresh produce supply chains. The synergistic effect of each link in the supply chain is promoted through the mutual cost sharing and coordination mechanism. However, the study did not consider the dual-channel decision-making problem. Zhang et al [6] constructed a dual-channel supply chain model in which a manufacturer sells products simultaneously through direct and retail channels, analyzed three blockchain adoption scenarios, and found that the blockchain adoption strategies of supply chain members are constrained by the unit blockchain operation cost, knowledge cost, and demand volatility.

Regarding the research on preservation efforts, studies have mostly focused on quality loss, quantity loss, and preservation efforts to reduce loss. Among the models based on spoilage rate or loss rate, Hsu [7] firstly proposed a perishable inventory model in which preservation inputs lead to a reduction in product spoilage rate, investigated the replenishment and preservation technology investment strategies for products with constant deterioration rate and demand, and gave a solution for optimal replenishment period, out-of-stock duration, order quantity, and preservation cost in order to maximize the unit revenue. Chen et al [2] assumed that the reseller's loss is an inverse function of the preservation effort and investigated the consignment strategy of the agricultural supply chain. Zheng et al [8] and Liu et al [9] assumed that the quantity loss of fresh agricultural products is a function of time, the former assumed that the product loss is an endogenous function of time; the latter used an exponential function to portray the relationship between the product's quantity loss and time. Cai et al [10] argued that providing freshness efforts during transportation in the supply chain can affect both quality and quantity loss, and developed a model to explore the optimality of centralized and decentralized decisions. In the model based on the dynamic change of freshness, Dan [11] used the product of initial freshness and preservation effort to portray the actual freshness of fresh produce, while Cao et al [12] assumed that the post-preservation freshness is a linear function consisting of the initial freshness, the level of preservation effort subjected to the preservation effort, and the coefficients of the influence of the preservation technology on preservation effect. On this basis, some scholars combined the time factor, Cao et al [13] hypothesized that the freshness of fresh produce decreases in a linear form with the increase of time within a certain period. Yue et al [14], Yu et al [15] believed that freshness is a dynamic process, and the preservation efforts of both sides of the supply chain can effectively delay the freshness decay, and they constructed a differential equation describing the dynamic change of freshness by drawing on the Nerlove-Arrow model proposed by El Ouardighi et al [16], which provides theoretical Support.

Regarding the research on supply chain coordination mechanism, since supply chain management is a complex process, members usually maximize their own interests during the decision-making process, which cannot achieve the optimal benefit of the supply chain system. Therefore, scholars have introduced contracts to coordinate the supply chain. Yang et al [17] In this paper, the optimization problem of preservation decision-making in fresh produce supply chain is investigated in the context of carbon trading, and a cost-sharing contract is designed to coordinate the supply chain. Yan et al [18] study the fresh produce supply chain consisting of manufacturers, distributors and retailers, and explore the optimal decision-making problem of all three under the environment of Internet of Things, and on the basis of this, the optimal decision-making problem is investigated. decision-making problem of the three, and based on this, proposed an improved gain-sharing contract to achieve supply chain coordination. Zhang et al [19] proposed a model based on the wholesale price contract and the revenue sharing contract, and found that the supply chain system can be optimized when the fair concern coefficient and the contract parameters are within a certain range. Lin et al [20] explored the optimal decision-making and coordination strategies for competitive supply chains in

the context of blockchain technology and found that both revenue-sharing contract and two-part pricing contract can lead the supply chain to a coordinated state, while the two-part pricing contract has a better fitness.

According to the above literature analysis, although the existing studies in the areas of fresh produce supply chain, preservation efforts and contract coordination have achieved certain results, the following shortcomings still exist: First, the micro-decision problem of supply chain members has not yet been studied in depth under the dynamic market environment; second, most of the studies are based on static single-cycle optimization, which does not adequately consider the long-term dynamic evolution characteristics of quality and demand; and third, it is generally assumed that the effect of preservation inputs on freshness is instantaneous, ignoring the natural decay characteristics of agricultural products. These issues provide a direction for future research to further deepen. Based on this, this paper draws on the dynamic freshness change differential equation proposed by Yue Liuqing et al [14,15] and introduces it into the model construction to more comprehensively represent the dynamic evolution of freshness in the time dimension, thus providing theoretical support for the analysis of the impact of freshness preservation efforts on supply chain decisions.

2. Model Assumptions

This chapter considers a supply chain model consisting of a fresh produce supplier and a retailer, where the fresh produce supplier acts as the dominant player and is responsible for the freshness of the fresh produce. In this model, the supplier sells fresh produce offline only through the retailer, and the retailer sells offline only. In this supply chain, the supplier determines the wholesale price $w(t)$, while the preservation of fresh produce requires continuous innovation in preservation technology, etc., to improve the freshness level of the produce, and thus also determines the preservation effort $K(t)$ of the produce, and the retailer determines its own retail price $p(t)$ based on the supplier's pricing.

Hypothesis 1: Freshness inputs improve the freshness of produce, but they also impose additional costs on produce, such as advances in freshness technology or product handling. According to Tang et al [21], there is a quadratic relationship between a supplier's freshness cost and its input effort:

$$C_s(t) = \frac{\mu}{2} K^2(t) \quad (1)$$

Hypothesis 2: Freshness is a key determinant of demand for fresh produce, and freshness is closely related to suppliers' freshness inputs. In this paper, drawing on the studies of Liu et al [9], Yue et al [14], and Yu et al [15], the freshness evolution process of fresh produce during the life cycle of fresh produce can be expressed as follows:

$$\dot{F}(t) = \theta K(t) - \gamma F(t), F(0) = F_0 \quad (2)$$

Where $F(t)$ denotes the freshness of fresh produce at time t , F_0 is the initial value, $K(t)$ denotes the preservation effort of the supplier at time t , θ denotes the influence coefficient of the preservation effort on the freshness of fresh produce, and γ is the attenuation factor, which is the natural attenuation of freshness.

Hypothesis 3: Consumers' preference for high freshness produce enhances their willingness to buy [22-24], and in conjunction with the existing literature [12], the demand functions for traditional distribution channels are respectively:

$$D(t) = \alpha - bp(t) + \lambda F(t) \quad (3)$$

Where $\alpha > 0$, $b \in (0,1)$, a larger b indicates that demand is more sensitive to price changes; $\lambda \in (0,1)$, the larger λ is, the higher the consumer's willingness to consume high levels of freshness.

Hypothesis 4: Discount coefficients for fresh produce suppliers and retailers between time t in continuous time, i.e., $\rho > 0$.

3. Mathematical Model

3.1 Centralized Decision-making Model

Under centralized decision-making, fresh produce suppliers and retailers can be regarded as different departments of the same enterprise. At this time, fresh produce suppliers and retailers are the same decision-making body. The long-term objective function of the supply chain is:

$$J^c = \max_{p,K} \int_0^\infty e^{-\rho t} \left\{ p(t)[\alpha - bp(t) + \lambda F^c(t)] - \frac{1}{2} \mu [K^c(t)]^2 \right\} dt \quad (4)$$

$$s.t. \dot{F}^c(t) = \theta K^c(t) - \gamma F^c(t)$$

Due to the complexity of solving the above model, the time t as a state does not affect the conclusion, and to simplify the writing, the time t will be omitted in this section (the same as below).

Proposition 1. The equilibrium solution for centralized decision-making is as follows.

(1) The equilibrium solution for the decision variables of each member of the supply chain is:

$$p^{c*} = \frac{\alpha + \lambda F^c}{2b} \quad (5)$$

$$K^{c*} = \frac{\theta(2q_1 F^c + q_2)}{\mu}$$

(2) The supply chain system optimal value is:

$$V^c = q_1 (F^c)^2 + q_2 F^c + q_3 \quad (6)$$

$$\begin{cases} q_1 = \frac{\mu(\rho + 2\gamma)}{4\theta^2} - \frac{\sqrt{b^2 \mu^2 (\rho + 2\gamma)^2 - 2\lambda^2 \theta^2 b \mu}}{4b\theta^2} \\ q_2 = \frac{\alpha \lambda \mu}{b\rho\mu + \sqrt{b^2 \mu^2 (\rho + 2\gamma)^2 - 2\lambda^2 \theta^2 b \mu}} \\ q_3 = \frac{(q_2)^2 \theta^2}{2\mu\rho} + \frac{\alpha^2}{4b\rho} \end{cases}$$

(3) The time evolution path of freshness of fresh produce is:

$$F^c = (F_0 - F_\infty^c) e^{-R_1 t} + F_\infty^c \quad (7)$$

Where $F_\infty^c = \frac{\theta^2 q_2}{\mu\gamma - 2q_1 \theta^2}$ and $R_1 = \frac{\mu\gamma - 2\theta^2 q_1}{\mu}$, F_∞^c are the steady-state values of the freshness of fresh

produce under concentrated scenarios. As time goes by $R_1 > 0$, that is, $0 < \lambda < \frac{\sqrt{b\mu\gamma(\rho + \gamma)}}{\theta}$, it

indicates that the steady-state value of freshness is globally stable, meaning that

$F_\infty^c = \frac{\alpha \theta^2 \lambda}{2b\gamma\mu(\gamma + \rho) - \theta^2 \lambda^2}$. Substituting the stabilized freshness value F_∞^c , it can be seen that when t

$\rightarrow \infty$, the steady state of each variable in Equations (6) and (7) is $p_\infty^c, K_\infty^c, V_\infty^c$.

Property 1 Under centralized decision making, the steady state function of each variable is compared with the steady state of the relevant parameter as:

$$\frac{\partial F_\infty^c}{\partial \alpha} > 0, \frac{\partial K_\infty^c}{\partial \alpha} > 0, \frac{\partial p_\infty^c}{\partial \alpha} > 0; \frac{\partial F_\infty^c}{\partial \theta} > 0, \frac{\partial K_\infty^c}{\partial \theta} > 0, \frac{\partial p_\infty^c}{\partial \theta} > 0$$

$$\frac{\partial F_\infty^c}{\partial \mu} < 0, \frac{\partial K_\infty^c}{\partial \mu} < 0, \frac{\partial p_\infty^c}{\partial \mu} < 0; \frac{\partial F_\infty^c}{\partial \lambda} > 0, \frac{\partial K_\infty^c}{\partial \lambda} > 0, \frac{\partial p_\infty^c}{\partial \lambda} > 0$$

From Property 1, it can be concluded that steady-state freshness, preservation inputs, and selling price increase with α , θ , and λ over the life cycle of fresh produce, and decreases with μ . When the contribution of freshness inputs to the freshness of produce is high, fresh produce suppliers will increase their investment in freshness in order to obtain higher wholesale prices, thereby providing produce with higher levels of freshness. This higher freshness of produce enables retailers to set higher selling prices relative to regular produce to reflect its quality advantage and market value. Freshness drives market demand for produce more significantly when the coefficient of consumer preference for freshness is large. In order to satisfy the market demand and obtain higher revenue, suppliers and retailers will increase their investment in freshness and set higher retail prices to maximize profits. However, when the freshness cost coefficient is high, the cost burden of freshness inputs rises significantly, leading to a significant increase in the unit cost of fresh produce. In this case, the decision makers in the operating companies will reduce the freshness inputs in order to reduce the costs, thus finding a balance between profits and costs.

3.2 Decentralized Decision-making Model

Under decentralized decision-making, both suppliers and retailers are rational and aim to maximize their respective interests when setting wholesale prices and freshness inputs as well as determining retail prices. The decision sequence is as follows: first, the supplier as the dominant player first sets the wholesale price of fresh produce $w(t)$ and fresh input $K(t)$, and the retailer sets $p(t)$ according to $w(t)$, and the long-term objective function of the supply chain members is modeled as:

$$\begin{aligned}
 J_s^n &= \max_{w,K} \int_0^\infty e^{-\rho t} \left\{ w(t)[\alpha - bp(t) + \lambda F^n(t)] - \frac{1}{2} \mu [K^n(t)]^2 \right\} dt \\
 \text{s.t.} \quad &\begin{cases} J_r^n = \max_p \int_0^\infty e^{-\rho t} \{ [p(t) - w(t)][\alpha - bp(t) + \lambda F^n(t)] \} dt \\ \dot{F}^n(t) = \theta K^n(t) - \gamma F^n(t) \end{cases}
 \end{aligned} \tag{8}$$

Proposition 2. The equilibrium solution for decentralized decision-making is as follows.

(1) The equilibrium solution for the decision variables of each member of the supply chain is:

$$\begin{aligned}
 w^{n*} &= \frac{\alpha + \lambda F^n}{2b} \\
 p^{n*} &= \frac{3\alpha + 3\lambda F^n}{4b} \\
 K^{n*} &= \frac{\theta(2m_1 F^n + m_2)}{\mu}
 \end{aligned} \tag{9}$$

(2) Supplier and retailer optimal profit and overall supply chain value is:

$$\begin{cases} V_s^n = m_1 (F^n)^2 + m_2 F^n + m_3 \\ V_r^n = n_1 (F^n)^2 + n_2 F^n + n_3 \\ V^n = (m_1 + n_1)(F^n)^2 + (m_2 + n_2)F^n + m_3 + n_3 \end{cases} \tag{10}$$

$$\begin{cases} m_1 = \frac{\mu(\rho + 2\gamma)}{4\theta^2} - \frac{\sqrt{b^2 \mu^2 (\rho + 2\gamma)^2 - \lambda^2 \theta^2 b \mu}}{4b\theta^2} \\ m_2 = \frac{\alpha \lambda \mu}{2b\rho\mu + 2\sqrt{b^2 \mu^2 (\rho + 2\gamma)^2 - \lambda^2 \theta^2 b \mu}}, \quad m_3 = \frac{(m_2)^2 \theta^2}{2\mu\rho} + \frac{\alpha^2}{8b\rho}; \\ n_1 = \frac{\mu \lambda^2}{16\sqrt{b^2 \mu^2 (\rho + 2\gamma)^2 - \lambda^2 \theta^2 b \mu}}, \quad n_2 = \frac{16bm_2 n_1 \theta^2 + \alpha \mu \lambda}{8b(\mu\rho - 2m_1 \theta^2 + \mu\gamma)} \\ n_3 = \frac{\alpha^2}{16b\rho} + \frac{n_2 m_2 \theta^2}{\mu\rho} \end{cases}$$

(3) The time evolution path of freshness of fresh produce is:

$$F^n = (F_0 - F_\infty^n)e^{-R_2 t} + F_\infty^n \quad (11)$$

Where $F_\infty^n = \frac{\theta^2 m_2}{\mu\gamma - 2m_1\theta^2}$, $R_2 = \frac{\mu\gamma - 2\theta^2 m_1}{\mu}$, F_∞^n are the steady-state values of the freshness of fresh produce under decentralized scenarios. As time goes by $R_2 > 0$, it indicates that the steady-state value of freshness is globally stable, meaning that $F_\infty^n = \frac{\alpha\theta^2\lambda}{-\theta^2\lambda^2 + 4b\gamma\mu(\gamma + \rho)}$. Substituting the stabilized freshness value F_∞^n , it can be seen that when $t \rightarrow \infty$, the steady state of each variable in Equations (9) and (10) is $w_\infty^n, p_\infty^n, K_\infty^n, V_{s\infty}^n, V_{r\infty}^n$.

Property 2 Under decentralized decision making, the steady state comparative analysis of the relevant parameters is:

$$\begin{aligned} \frac{\partial F_\infty^n}{\partial \alpha} > 0, \frac{\partial K_\infty^n}{\partial \alpha} > 0, \frac{\partial w_\infty^n}{\partial \alpha} > 0, \frac{\partial p_\infty^n}{\partial \alpha} > 0; \frac{\partial F_\infty^n}{\partial \theta} > 0, \frac{\partial K_\infty^n}{\partial \theta} > 0, \frac{\partial w_\infty^n}{\partial \theta} > 0, \frac{\partial p_\infty^n}{\partial \theta} > 0; \\ \frac{\partial F_\infty^n}{\partial \mu} < 0, \frac{\partial K_\infty^n}{\partial \mu} < 0, \frac{\partial w_\infty^n}{\partial \mu} < 0, \frac{\partial p_\infty^n}{\partial \mu} < 0; \frac{\partial F_\infty^n}{\partial \lambda} > 0, \frac{\partial K_\infty^n}{\partial \lambda} > 0, \frac{\partial w_\infty^n}{\partial \lambda} > 0, \frac{\partial p_\infty^n}{\partial \lambda} > 0; \end{aligned}$$

Under decentralized decision making, the relationships of each decision variable of supply chain members with market capacity, contribution of freshness inputs to produce freshness, cost of freshness effort coefficient, and consumer freshness preference coefficient are consistent with the situation under **Property 2** centralized decision making.

3.3 Comparative Analysis

From Propositions 1 and 2, it follows that $F_\infty^c > F_\infty^n, K_\infty^c > K_\infty^n$

Property 3 The level of freshness of fresh produce and the optimal preservation effort of suppliers are higher in the centralized decision than in the decentralized decision. This is because the supplier's freshness effort depends mainly on the expected benefits from increasing freshness effort compared to the cost of freshness. Therefore, in the centralized decision, suppliers and retailers cooperate to improve fresh produce freshness as a common goal. Whereas in decentralized decision making, the supplier has to bear the cost of freshness alone, and in order to save cost, the supplier will reduce the freshness input, resulting in a decrease in the freshness level of fresh produce.

From Propositions 1 and 2, it follows that $V_\infty^c > V_\infty^n$

Property 4 Under centralized decision-making, the total profit of the supply chain is always higher than that of decentralized decision-making. This is because in decentralized decision-making, supply chain members work individually, which leads to double marginal effect, which is not conducive to product market development in the long run, and ultimately makes the total profit of the supply chain decrease. In the centralized decision-making scenario, this problem does not exist because all decisions are made from the perspective of profit maximization of the overall supply chain (suppliers and retailers as a whole, i.e., two cooperating divisions of an organization). Therefore, supply chain members should be encouraged to cooperate.

4. Cost-sharing Compacts

Under the freshness cost-sharing model, the freshness cost-sharing ratio ϕ determines the allocation of freshness costs between suppliers and retailers of fresh produce, when suppliers bear $\frac{1}{2}\phi\mu[K^f(t)]^2$ and retailers bear $\frac{1}{2}(1-\phi)\mu[K^f(t)]^2$.

Under the freshness cost-sharing contract model, the profits of fresh produce suppliers and retailers are respectively

$$\begin{aligned}
 J_s^f &= \max_{w,K} \int_0^\infty e^{-\rho t} \left\{ w(t)[\alpha - bp(t) + \lambda F^f(t)] - \frac{1}{2}\phi\mu[K^f(t)]^2 \right\} dt \\
 \text{s.t.} \begin{cases} J_r^f = \max_p \int_0^\infty e^{-\rho t} \left\{ [p(t) - w(t)][\alpha - bp(t) + \lambda F^f(t)] - \frac{1}{2}(1-\phi)\mu[K^f(t)]^2 \right\} dt \\ \dot{F}^f(t) = \theta K^f(t) - \gamma F^f(t) \end{cases} \quad (12)
 \end{aligned}$$

Proposition 3. The equilibrium solution for cost-sharing compacts is as follows.

(1) The equilibrium solution for the decision variables of each member of the supply chain is:

$$\begin{aligned}
 w^{f*} &= \frac{\alpha + F^f \lambda}{2b} \\
 p^{f*} &= \frac{3(\alpha + F^f \lambda)}{4b} \\
 K^{f*} &= \frac{(2F^f l_1 + l_2)\theta}{\mu\phi}
 \end{aligned} \quad (13)$$

(2) Supplier and retailer optimal profit and overall supply chain value is:

$$\begin{cases} V_s^f = l_1(F^f)^2 + l_2 F^f + l_3 \\ V_r^f = f_1(F^f)^2 + f_2 F^f + f_3 \\ V^f = (l_1 + f_1)(F^f)^2 + (l_2 + f_2)F^f + l_3 + f_3 \end{cases} \quad (14)$$

$$\begin{cases} l_1 = \frac{\mu \left(2\gamma + \rho - \rho \sqrt{\left(1 + \frac{2\gamma}{\rho} \right)^2 - \frac{\theta^2 \lambda^2}{b\mu\rho^2\phi}} \right) \phi}{4\theta^2}, \quad l_2 = \frac{\alpha\lambda}{2b\rho \left(1 + \sqrt{\left(1 + \frac{2\gamma}{\rho} \right)^2 - \frac{\theta^2 \lambda^2}{b\mu\rho^2\phi}} \right)} \\ l_3 = \frac{\alpha^2}{8\rho b} + \frac{4l_2^2\theta^2}{8\rho\mu\phi}; \quad f_1 = \frac{32bl_1^2\theta^2(-1+\phi) + \lambda^2\mu\phi^2}{16b\phi(-4l_1\theta^2 + \mu(2\gamma + \rho)\phi)} \\ f_2 = \frac{\alpha\lambda\mu\phi^2 + 16bl_2\theta^2(l_1(-1+\phi) + f_1\phi)}{8b\phi(-2l_1\theta^2 + \mu(\gamma + \rho)\phi)}, \quad f_3 = \frac{\alpha^2\mu\phi^2 + 8bl_2\theta^2(l_2(-1+\phi) + 2f_2\phi)}{16b\mu\rho\phi^2} \end{cases}$$

(3) The time evolution path of freshness of fresh produce is:

$$F^f = (F_0 - F_\infty^f)e^{-R_3t} + F_\infty^f \quad (15)$$

Where $F_{\infty}^f = \frac{\theta^2 l_2}{\phi \mu \gamma - 2 l_1 \theta^2}$, $R_3 = \gamma - \frac{2 \theta^2 l_1}{\mu \phi}$, F_{∞}^n are the steady-state values of the freshness of fresh produce under cost-sharing compacts. As time goes by $R_3 > 0$, it indicates that the steady-state value of freshness is globally stable, meaning that $F_{\infty}^f = \frac{\alpha \theta^2 \lambda}{-\theta^2 \lambda^2 + 4 b \gamma \mu (\gamma + \rho) \phi}$. Substituting the stabilized freshness value F_{∞}^f , it can be seen that when $t \rightarrow \infty$, the steady state of each variable in Equations (13) and (14) is $w_{\infty}^f, p_{\infty}^f, K_{\infty}^f, V_{s\infty}^f, V_{r\infty}^f$.

In addition, all the control curves are monotonic with respect to time. When $F_0 > F_{\infty}^f$, the fresh produce price curve is monotonically decreasing with respect to time, this implies that fresh produce supply chain members will adopt a skimming pricing strategy, and when $F_0 < F_{\infty}^f$, the fresh produce price curve is monotonically increasing with respect to time, this implies that fresh produce supply chain members will adopt a penetration pricing strategy.

5. Numerical Analysis

In order to verify the accuracy of the conclusions of this chapter, this paper uses Matlab software to verify the conclusions of this chapter through the relevant literature, combined with actual cases and the relationship between the range of variables in this paper, and the specific assignment of the parameters are as follows: $\alpha = 1, b = 0.1, \lambda = 0.1, \mu = 4, \sigma = 2, \theta = 0.5, \gamma = 0.2, \rho = 0.1$.

5.1 Impact of Consumer Freshness Preferences on Supply Chain Decisions

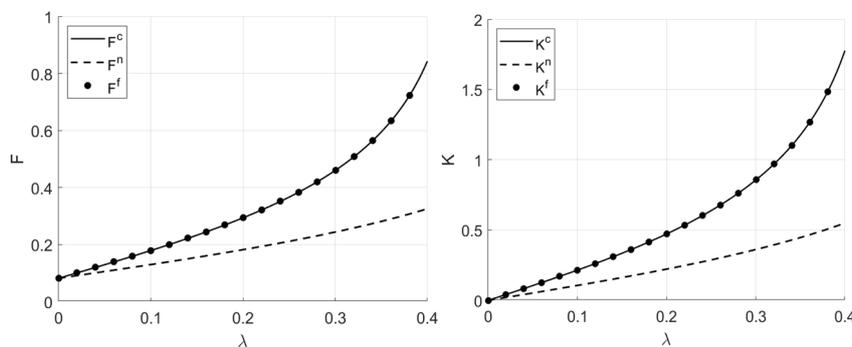


Fig 1. Impact of λ on product freshness Fig 2. Impact of λ on preservation prices

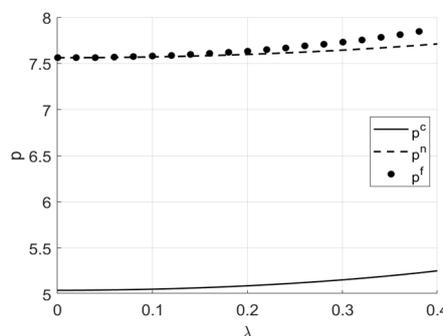


Fig 3. Impact of λ on selling efforts

Fig. 1 and 2 demonstrate the impact of consumer freshness preference coefficients on produce freshness and preservation efforts, respectively. It can be found through the analysis that consumer freshness preference has a significant effect on the key decision variables of the supply chain under different decision-making modes, and the centralized decision-making, decentralized decision-making and cost-sharing contract modes show significant differences. Under the centralized decision-

making model, product freshness and preservation effort increase rapidly with the increase of consumer freshness preference, showing a significant non-linear growth trend. Under the cost-sharing contract model, product freshness and preservation effort also increase with the increase of consumer freshness preference coefficient. Notably, when the cost-sharing coefficient = 0.5, the freshness effort and product freshness under the contract at this point are equal to the results of centralized decision making, indicating that the same effect as centralized decision making can be achieved through appropriate contract design. In addition, in the decentralized decision-making model, the increase in each variable is significantly smaller than in the centralized decision-making and cost-sharing contract models. Fig. 3 shows the effect of consumer freshness preference on sales price. In the centralized decision-making model, the selling price rises with increasing consumer freshness preference. In the cost-sharing compact model, the trend of sales price increase is similar to that of centralized decision making. Whereas, under the decentralized decision-making model, the selling price is minimized.

5.2 Impact of the Extent to Which Preservation Efforts Affect Freshness on Supply Chain Decisions

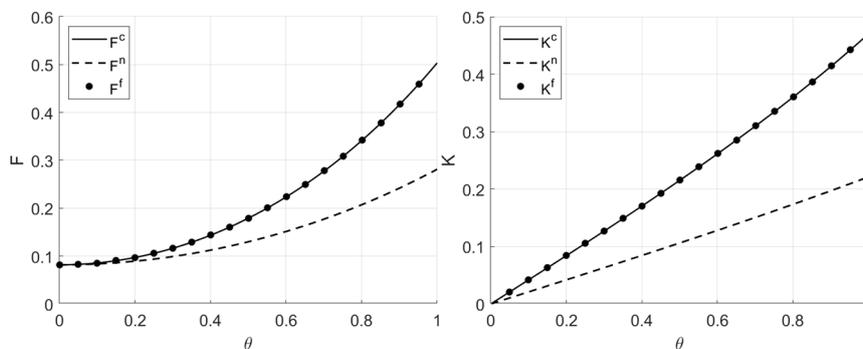


Fig 4. Impact of θ on product freshness **Fig 5.** Impact of θ on preservation efforts

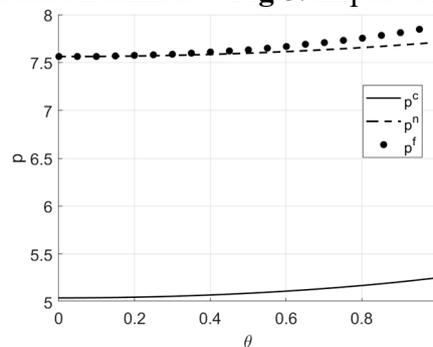


Fig 6. Impact of θ on selling prices

It can be observed from Fig. 4 that product freshness gradually increases with the increase in the degree of influence of preservation effort, regardless of whether it is under centralized decision making, decentralized decision making, or cost-sharing pact. This suggests that fresh produce suppliers are more motivated to make freshness effort investment when the effect of freshness effort on freshness is more significant, thus significantly improving the freshness level of the product. Fig. 5 shows that the level of freshness effort likewise increases significantly with the increase in the level of impact of freshness effort. This is because supply chain members are more willing to increase their freshness investment to obtain higher benefits when the efficiency of freshness effort in enhancing product freshness increases. In addition, centralized decision-making can maximize the overall supply chain benefits through cooperation, and thus suppliers are willing to invest more freshness efforts; while the cost-sharing contract mitigates the problem of insufficient freshness efforts under decentralized decision-making to a certain extent. As shown in Fig 6, the selling price also shows a certain increasing trend with the increase of the degree of influence of preservation efforts.

5.3 Dynamic Relationship between Supply Chain Members' Profit

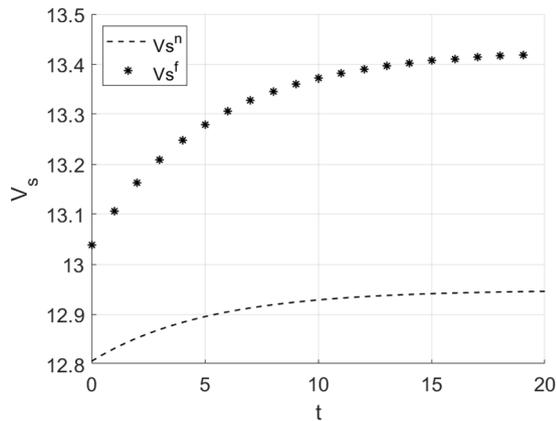


Fig 7. Impact of the t on retailer profits

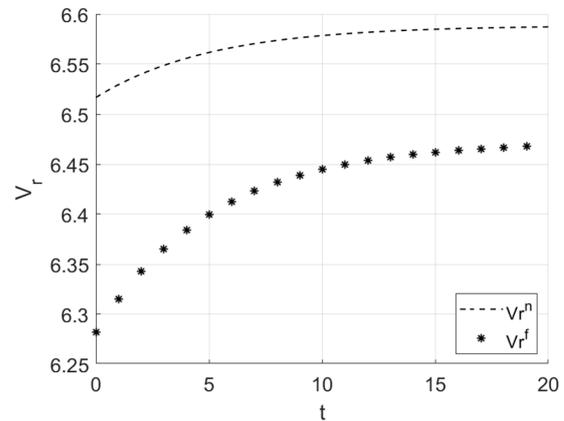


Fig 8. Impact of the t on supplier profits

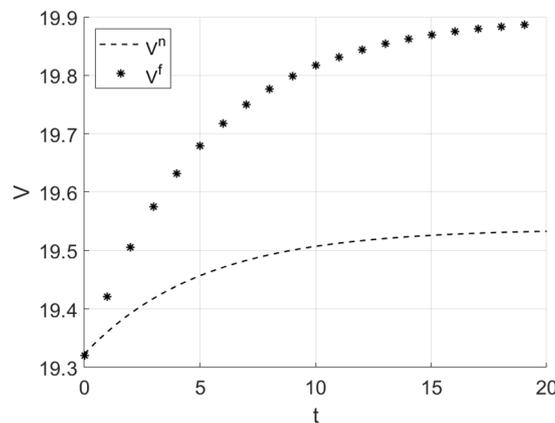


Fig 9. Impact of the t on total supply chain profit

As can be seen in Figures 7, 8 and 9, the cost-sharing pact achieves significant improvements in enhancing the overall efficiency of the supply chain. From Fig. 7, it can be seen that suppliers' profits are consistently higher under the cost-sharing pact than under the decentralized decision. From Fig. 8, it can be seen that the retailer's profit decreases under the cost-sharing pact, probably due to the fact that the cost-sharing agreement favors more incentives to the supplier. Finally, Fig. 9 demonstrates that total supply chain profits are significantly higher under the cost-sharing pact than under the decentralized decision and stabilize with gradual growth over time. This result verifies the improvement effect of the cost-sharing pact on the overall profit of the fresh produce supply chain, and in general, the cost-sharing pact significantly improves the overall profitability of the fresh produce supply chain through a rational cost allocation mechanism.

6. Conclusion

In this chapter, a differential game model of centralized and decentralized decision-making is developed in the context of fresh produce supply chain, taking into account suppliers' freshness inputs and consumers' freshness preferences, subdividing the parameters of consumers' freshness preferences, the degree of influence of freshness efforts on freshness on the supply chain decision-making impacts as well as the dynamics of supply chain members' profits. Further, the coordination problem of fresh produce supply chain is studied from a dynamic perspective, and a cost-sharing contract is designed to finally realize supply chain improvement. The specific findings are as follows:

Consumers' freshness preference has a significant positive effect on product freshness level and preservation efforts, and it is particularly evident in the centralized decision-making model. Centralized decision-making optimizes the overall efficiency through cooperation among supply chain members and significantly improves the freshness input and product freshness level. Under the cost-sharing contract model, the levels of product freshness and freshness effort are between centralized and decentralized decision-making, indicating that a reasonable cost-sharing mechanism can effectively motivate supply chain members to increase freshness input. In contrast, under the decentralized decision-making model, the lack of coordination mechanism and insufficient preservation input lead to the lowest level of product freshness, which makes it difficult to satisfy consumers' demand for high-freshness products. The cost coefficient of preservation effort has a significant negative effect on product freshness and preservation effort, and the centralized decision-making model alleviates the upward pressure on costs by optimizing resource allocation; while the cost-sharing contract model effectively improves the inefficiency problem under decentralized decision-making by reducing the burden of individual costs. In addition, as the price elasticity coefficient increases, product freshness and preservation effort significantly decrease. The centralized decision-making model mitigates the negative impact of increased price sensitivity to a certain extent, while the cost-sharing contract provides greater incentives for freshness improvement by sharing the cost of freshness, and performs better compared to the decentralized decision-making model. The levels of product freshness and preservation effort gradually increase and stabilize over time, with the highest final level in the centralized decision-making model, the second highest in the cost-sharing pact, which is close to the centralized decision-making model, and the lowest final level in the decentralized decision-making model. By rationally allocating supply chain costs and benefits, the cost-sharing pact makes the suppliers' profit higher than the decentralized decision-making mode, but the retailers' profit lower than the decentralized decision-making mode, which, in general, significantly improves the overall supply chain efficiency, and the overall efficiency gradually tends to be stabilized. In addition, optimizing the cost-sharing coefficient can further approach the optimal benefit level of centralized decision-making, which provides effective support for the long-term stable development of the supply chain.

This paper takes the supply chain of a single fresh produce supplier and a single retailer as the object of study, however, in practice, a certain agricultural product may involve multiple suppliers and multiple retailers, and there are competitive and cooperative relationships among different supply chain members. In the future, we can further expand the study on the dynamic game mechanism of competition between multiple suppliers and multiple retailers in a common market, focusing on the equilibrium strategy of supply chain decision-making under the cooperative competition mode and its impact on market efficiency.

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