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# A differential game model research on dynamic pricing and coordination of fresh agricultural products supply chain based on freshness

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**ABSTRACT**

For the problem of optimal dynamic pricing and coordination of fresh agricultural products supply chain, the differential equations related to freshness and market needs are constructed, and the optimal control theory is used to solve the optimal strategy under centralized and decentralized decision-making, i.e., optimal selling price and optimal preservation input. The equilibrium results under the two scenarios are also compared. The comparison finds that the decentralized scenario leads to low overall supply chain profits, based on which a two-part pricing contract is proposed to coordinate the supply chain operating companies. The results show that freshness effectiveness directly impacts pricing, and the centralized scenario does not necessarily lead to high prices for fresh produce due to the 'double marginal effect'. the two pricing contracts can successfully coordinate the supply chain. The freshness effectiveness increases the supply chain coordination ability of fresh produce suppliers, while operational inefficiencies, on the contrary, decrease the coordination ability.

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## 1. Introduction

With the continuous improvement of residents' eating habits and quality of life, the selling price of agricultural products is no longer the only factor that residents pay attention to when purchasing, and people pay more attention to its quality, which is reflected in the fact that consumers are more inclined to buy agricultural products with high freshness. Lu et al. (2019) believe that consumer utility is a function of the freshness and price of agricultural products. Although there are differences in the initial awareness of the freshness of agricultural products by different consumers, consumers are buying more products as the freshness of agricultural products decreases. The utility obtained later is also reduced.

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Freshness is closely related to the quality of fresh produce and is an essential indicator of its quality (Cai et al., 2010). There is no unified definition of the concept in the academic field, and its meaning could be more transparent. Both enterprises nor academia recognizes no specific norms regarding identification techniques and methods. In general, freshness can be reflected by the external appearance, color, and taste of fresh produce (e.g., vegetables and fruits), which consumers can directly perceive. For example, people tend to judge the freshness of vegetables such as cabbage based on their appearance and color, aquatic products such as fish and shrimp based on their freshness, and poultry products such as pork based on their color and taste.

Research shows that price is an essential factor influencing demand (Anderson et al., 2013; Kalambokidis, 2012; Scobie, 1989), and the selling price and freshness of fresh produce are the two key elements affecting its market demand (Chen et al., 2022; Lu et al., 2019; Luo et al., 2021). Lu et al. (2019) used the freshness factor to characterize its quality $\theta(t) = \theta^t$, Luo et al. (2021) added the natural attenuation coefficient and preservation effort coefficient of fresh agricultural products to describe their quality loss function $\theta(t) = \theta^{(\alpha - f(\gamma))t}$, although scholars describe the freshness of agricultural products from different perspectives, they all believe that the market demand for fresh agricultural products depends on both its freshness and its price. According to the research of Tsiros and Heilman (2005), Yan et al. (2020), and Liu et al. (2021a), consumers' purchase intention or behavior will decrease with the decrease in the freshness of fresh agricultural products. Low consumer purchase intention is lower. Herbon et al. (2017) believe that consumers are sensitive to the freshness of fresh agricultural products, but different consumers have different sensitivities to freshness. Therefore, Cai et al. (2010) and Liu et al. (2021a) believe preservation efforts can effectively prolong its freshness.

In practice, companies operating in the agricultural supply chain will sell products with different freshness levels (Herbon, 2016; Xu et al., 2022) since fresh agricultural products can be directly sensed by human sight and smell. As a result, consumers have to purchase solid intentions or behaviors for obviously or relatively fresh vegetables, fruits, and fresh aquatic products and lose interest in fresh agricultural products that are about to pass the preservation period (close to the processing period). At the same selling price, the freshness of the product determines the consumer's preference for it (consumers are willing to pay for fresh produce). Cai et al. (2010) believe that the freshness of agricultural products is proportional to the sales price. Consumers are willing to pay higher prices for high-fresh produce. Therefore, to satisfy consumers' preference for the freshness of fresh agricultural products, supply chain operators of fresh agricultural products need to pay higher costs for their preservation.

Based on the above background, this paper considers the fresh agricultural products provided by fresh agricultural product supply chain operators for sale. Under the circumstance that the market demand depends on the freshness and price of fresh agricultural products at the same time, the operating enterprise adopts the optimal/balanced dynamic pricing and the level of fresh-keeping effort input (referred to as the input of fresh-keeping in this paper) to maximize its profits. Some scholars have intensely discussed the pricing of fresh agricultural products supply chain and the input of freshness. However, they have ignored the delayed effect of freshness input on demand, and that freshness decays with freshness input and natural decay. That is, the dynamic effect is ignored. Additionally, operational inefficiencies are not considered. Operational inefficiency depicts that the unit production cost of fresh agricultural products will increase with fresh-keeping input, resulting in lower operational efficiency for supply chain operators. Furthermore, the coordination between enterprises operating in the dynamic fresh agricultural product supply chain is rarely studied. In response to the above situation, this paper specifically discusses the following questions: (1) What are the optimal/equilibrium pricing and fresh-keeping input strategies under the two scenarios of concentration and decentralization? (2) How do preservation inputs and operational inefficiencies affect optimal/equilibrium strategies? (3) What kind of contract is designed to coordinate the fresh produce supply chain perfectly?

This paper considers a secondary fresh agricultural product supply chain in a dynamic environment to solve the above problems. Suppliers determine the wholesale price and fresh-keeping input of fresh agricultural products, and retailers determine the sales price of fresh agricultural products. First, the optimal/balanced dynamic pricing and fresh-keeping input strategies for fresh agricultural products are given under centralized and decentralized scenarios. They are second, comparing the equilibria under the centralized and decentralized scenarios. Third, two gradings (two pricing) contracts are proposed to coordinate the supply chain of fresh agricultural products. The primary research shows that the equilibrium strategy (freshness and profit) under the centralized scenario is higher than that under the decentralized scenario, and the selling price of agricultural products under the centralized scenario may be lower or higher than that under the decentralized decision-making, which mainly depends on Fresh agricultural product supply chain system parameters. Two pricing contracts can perfectly coordinate the supply chain. Preservation effectiveness improves fresh produce suppliers' supply chain coordination ability, while operational inefficiency weakens their coordination ability.

This paper uses the differential game approach to model and solve the related problems. The application of differential games in the field of optimal control of supply chain management has apparent advantages. First, the differential game is unique in that the phenomenon (description of the situation of the decision-maker of the operating company facing the decision object) is described by differential equations in the game between the decision-makers of the supply chain operating companies. At any given moment, the control variable is the variable that the decision-maker considers when making a decision. This variable plays a vital role in the decision, and its change also affects the state variable. The state variable is the environment in which the decision-maker is placed, i.e., the scenario in which the decision-maker makes the decision. For example, in the freshness model, the control variable is the freshness input, and the freshness is the state variable.

Furthermore, in the objective generalized model, the supply chain profit function maximization is the performance indicator of the decision-maker. The differential game not only reflects the effect of freshness input on freshness but also can simulate the dynamic change process of freshness with freshness input of fresh produce business enterprises (mainly suppliers); secondly, the strategy solution reflects the behavioral relationship among members, and the feedback equilibrium reflects that the optimal strategy derived by suppliers and retailers depends on the initial state (initial value of freshness) and current time. Under the equilibrium strategy, the supplier considers the dynamic change of freshness, adjusts its strategy under the retailer's decision, and finally realizes the coordination among operating companies.

The novelty of this method is reflected in the following aspects: (i) Since the freshness of agricultural products is affected by the level of preservation efforts and natural decay, it is more appropriate to use dynamic equations to express the freshness of fresh agricultural products, and this method is relatively novel. (ii) The supplier determines the wholesale price and the retailer determines the sales price according to the freshness of agricultural products to set dynamic prices, and the supplier and the retailer in the pricing process. There is a conflict of interest between the supplier and the retailer in the pricing process, and there is a game between the two. The game sequence follows: the supplier announces the wholesale price of fresh agricultural products and freshness input, and then the retailer decides the selling price. (iii) The two-part pricing contract model designed by the supplier can perfectly coordinate the supply chain. The contributions of this paper are as follows. (i) Inform the development of pricing strategies for fresh produce operations, such as penetration pricing or skimming pricing for retailers. (ii) Provide a basis for suppliers to develop reasonable two-part pricing contracts. (iii) Provide a basis for reconciling supplier and retailer margins. (iv) Provide a basis for suppliers to develop freshness preservation input strategies, where suppliers aim to maximize their profits and suppliers through freshness efforts to provide retailers with products that feel fresher in order to obtain higher wholesale prices, so fresh produce suppliers develop freshness input strategies to ensure the freshness of produce.

The innovation points of this paper are as follows. (i) The core of the game between fresh produce suppliers and retailers is pricing, and the pricing is based on the freshness of the produce, which is a dynamic change process, so the game process between suppliers and retailers is a dynamic change process. (ii) The two pricing contracts use the Nash negotiation model to determine the value of the wholesale price. (iii) Freshness effectiveness and operational inefficiency have an impact in terms of pricing, freshness inputs, profitability, and equally in terms of fresh produce supply chain coordination.

The game in this paper is a Stackelberg differential game, in which the fresh produce supplier plays the leading role in the supply chain, and the retailer plays the following role accordingly. The game sequence follows: the supplier first announces the wholesale price of fresh produce $w(t)$ and freshness input $u(t)$, and then the retailer decides the selling price of fresh produce $p(t)$. The retailer decides the selling price based on the freshness of the products the supplier provides. The supplier decides the wholesale price and freshness input strategy based on the retailer's selling price. The freshness input determines the freshness of the produce, the freshness determines the price, and the price determines the profit. The operating companies need to coordinate before getting the profit they want. Freshness is a dynamic process; therefore, the game between suppliers and retailers is dynamic. However, the differential game is very suitable for modeling the related process.

For example, Liu et al. (2015) constructed a differential equation for dynamic product quality level: $\dot{Q}(t) = I(t) - \sigma Q(t), Q(0) = Q_0$, where $Q(t)$ is the product quality level and $I(t)$ is the product innovation, and also constructed a differential equation for product goodwill: $\dot{G}(t) = A(t) + \theta Q(t) - \delta G(t), G(0) = G_0$, where $G(t)$ is the product goodwill and $A(t)$ denotes the advertising rate, based on which the optimal under centralized and decentralized scenarios were calculated Liu et al. (2015) is related to this paper, but there are differences between this paper and this paper, the difference is that there are similar ideas in constructing dynamic change differential equations, and there are conflicts of interest between suppliers and retailers, and the game process between them is a dynamic change process. The game process is a dynamic change process; the difference is that this paper by Liu et al. (2015) is based on the current-value Hamiltonians method for calculation, while this paper uses the HJB method. This paper also analyzes the effect of preservation effectiveness and operational inefficiency on pricing decisions in the numerical sensitivity analysis, which Liu et al. (2015) need to analyze in this paper.

In summary, the most innovative aspect of this paper is that the effects of freshness preservation effectiveness and operational inefficiency on dynamic pricing and coordination of operating companies are investigated.

In this paper, Sec. 1 describes the problem background; Sec. 2 model building, describes the optimal fresh produce dynamic pricing problem of operating firms under freshness and constructs the corresponding model; Sec. 3 solves the optimal fresh produce dynamic pricing and fresh produce input strategy of operating firms using optimal control theory for fresh produce supply chain operating firms' preservation inputs and operational inefficiencies; Sec. 4 equilibrium comparison under two scenarios; Sec. 5 presents a two-part pricing fresh produce supply chain coordination; Sec. 6 presents a numerical analysis; Sec. 7 summarizes and gives conclusions and management inspirations.

## 2. Model building

### 2.1. Model fits

The symbols used are shown in Table 1.

### 2.2. Model description

This article considers a fresh produce supplier $s$ and a fresh produce retailer $r$. The secondary supply chain formed by the fresh agricultural product suppliers decides the

**Table 1.** Compliance description.

| Conform to | Meaning | Conform to | Meaning |
|---|---|---|---|
| $g(t)$ | Freshness (state variable) | $g_0$ | Initial freshness value |
| $u(t)$ | Freshness input (control variable) | $c_{s0}, c_{r0}, c_1$ | Supplier and retailer initial unit costs and operational inefficiencies |
| $w(t)$ | Wholesale price (control variable) | $\lambda$ | Effective coefficient of fresh-keeping input |
| $p(t)$ | Sales price (control variable) | $\delta$ | Freshness natural attenuation coefficient |
| $c_s(t), c_r(t)$ | Supplier and retailer produce unit costs | $\eta$ | Freshness input cost factor |
| $D(t)$ | Demand rate of fresh agricultural products | $\rho$ | The time discount factor is the discount rate |
| $J_S, J_R$ | Supplier and retailer profits | $a$ | Fresh produce market potential |
| $b$ | Price elasticity | $\theta$ | Freshness contribution rate coefficient |

input of freshness preservation $u(t)$ and wholesale price $w(t)$, fresh produce retailers decide retail prices $p(t)$, and $g(t)$ indicates the freshness of fresh produce.

As consumers tend to buy agricultural products with high freshness, suppliers of fresh agricultural products have begun to invest in preservation actively. For example, the innovation of fresh-keeping technology is invested in improving the freshness of agricultural products to attract consumer demand (Liu et al., 2021b; Luo et al., 2022). Since the advancement of preservation technology can continuously ensure the preservation of agricultural products, it is more realistic to describe the freshness of agricultural products dynamically. On the other hand, agricultural products are perishable products that will naturally decay over time, which is the decay of freshness. In short, the freshness of agricultural products increases with not only the investment in fresh-keeping but also the freshness of agricultural products when they reach the sales terminal (supermarket, community convenience store). The longer the shelf life of the sale, and the rotten with the natural decay, however, in the life cycle of fresh agricultural products $[0, T](T < \infty)$, the evolution process of the freshness of fresh agricultural products (including the time from production to sale) is expressed as:

$$\dot{g}(t) = \lambda u(t) - \delta g(t), g(0) = g_0 \tag{1}$$

Consumers' preference for freshness increases their willingness to purchase high-freshness agricultural products, resulting in a positive relationship between freshness and demand for fresh agricultural products. The higher the freshness or fresher, the higher the demand. Therefore, the demand function for fresh agricultural products is expressed as:

$$D(t) = a - bp(t) + \theta g(t) \tag{2}$$

In order to obtain a positive equilibrium result, the parameters of Eq. (2) should satisfy: $a > bc_0$ (Zhang et al., 2017). This means that when the retail price of fresh produce is $p(t)$, equal to the minimum production cost $c_0 = c_{s0} + c_{r0}$, and when the freshness is zero, the demand is buoyant (Martín-Herrán & Taboubi, 2015; Bayramoglu et al., 2018). This linear demand function is ubiquitous in fresh produce supply chain management, such as Groznika and Trkman (2012), Yang and Tang (2019), Liu et al. (2021a), Liu et al. (2021b), Rani et al. (2022), and other pieces of literature.

The input of fresh-keeping improves the freshness of agricultural products, but at the same time, it also brings additional costs to agricultural products, such as product handling or cost control (Deng et al., 2011; Wang & Li, 2012; Chen et al., 2022). Specifically, the higher the freshness of agricultural products, the more fresh-keeping technology investment is required, which makes fresh agricultural product suppliers bear high unit production costs. Therefore, the variable unit cost of fresh produce suppliers and retailers can be expressed as:

$$c_s(t) = c_{s0} + c_1 g(t), c_r(t) = c_0 - c_{s0} = c_{r0} \tag{3}$$

In $c_{s0}, c_{r0}$ is the initial unit cost of fresh produce suppliers and retailers. For the convenience of calculation, it is assumed that the variable unit cost of the retailer is the initial unit cost, and $c_0 = c_{s0} + c_{r0}$ is the initial unit cost of fresh agricultural products. $c_1$ is the marginal cost of the fresh agricultural product supplier's investment in fresh-keeping to improve the freshness, called the supplier's operational inefficiency coefficient. For example, Liu et al. (2021c) believed that the empty load rate of vehicles used for fresh-keeping (cold chain) transportation of agricultural products is high when returning. The phenomenon of resource idleness is serious. That is, supply and demand matching efficiency is low, and the marginal cost of cold chain transportation is increased, that is, the marginal cost of fresh-keeping. Zhang et al. (2016) used the operational inefficiency coefficient to characterize the variable unit cost of green products produced by green manufacturers. However, more literature is needed to study the variable unit cost of fresh produce in combination with operational inefficiencies. In order to obtain a positive equilibrium result, in (3) $c_1$ need to meet: $0 < c_1 < \frac{\theta}{b}$, $c_1$ the larger the value, the less efficient the fresh produce preservation process is.

This linearly increasing cost function is widely used by scholars in green products, pharmaceuticals other industries, such as De Giovanni (2011), Zhang et al. (2016), Papalexi et al. (2020), and Deng et al. (2022). However, the existing literature is rarely used on the cost of agricultural products. However, when $c_1 = 0$ to, the operational inefficiency of the operating enterprise does not exist, and the unit cost of fresh agricultural products is a fixed constant, that is, the initial unit cost.

In the field of operation management, the input cost is assumed to be a quadratic function (Karray, 2015; Liu et al., 2015); that is, the supplier's fresh-keeping input cost function is expressed as:

$$C(u(t)) = \frac{\eta}{2}u^2(t) \tag{4}$$

In $\eta$ is the supplier's input cost factor for preservation. Equation (4) is a quadratic function relationship between the fresh-keeping cost and the fresh-keeping input of the fresh agricultural product supply chain operation enterprise.

The convex cost function describes the diminishing marginal returns of the operating enterprise's freshness input (Liu et al., 2021c; Luo et al., 2021; Nguyen & Ngo, 2021; Guo et al., 2022), indicating that in order to achieve a certain level of freshness, the operating enterprise needs to bear lower costs initially, but in order to achieve a higher level of freshness. With a high level of freshness, fresh agricultural product supply chain operators need to bear more costs.

In the life cycle of fresh produce $[0, T]$, the supplier objective functional is:

$$J_S = \int_0^T e^{-\rho t}\left(\left(w(t) - c_{s0} - c_1 g(t)\right)\left(a - bp(t) + \theta g(t)\right) - \frac{\eta}{2}u^2(t)\right)dt \tag{5}$$

The retailer's target functional is:

$$J_R = \int_0^T e^{-\rho t}\left(\left(p(t) - w(t) - c_{ro}\right)\left(a - bp(t) + \theta g(t)\right)\right)dt \tag{6}$$

In $\rho$ is the discount rate.

Under the feedback information structure, the strategy of each operating enterprise in the fresh agricultural product supply chain is feedback; it shows that the pricing of agricultural products and the input strategy of fresh-keeping are time-consistent (the wholesale price of the supplier's decision and the retail price of the retailer's decision are consistent in time with the decision of fresh-keeping), and only depends on the state variable freshness $g(t)$ of current produce freshness levels. In the differential game under the life cycle of fresh agricultural products, it is a common assumption to obtain the solution in the steady state, that is, the stable value (Lu et al., 2019).

## 3. Model solving

In this section, the optimal strategies under both centralized and decentralized scenarios are studied with the help of game theory and the Hamilton-Jacobi-Bellman (HJB) equations. First, the equilibrium strategy under the centralized scenario is studied. The fresh agricultural product supply chain operators jointly decide the selling price and the fresh-keeping input strategy to maximize the overall supply chain profit. Second, the optimal strategy under the decentralized scenario is analyzed; that is, the supplier decides the wholesale price and preservation input strategy, retailer decides the selling price.

### *3.1. Equilibrium strategies in concentrated scenarios*

In the centralized scenario, suppliers and retailers in the fresh produce supply chain reach a binding cooperation agreement, which provides a basis for decision-making for both partners. Therefore, suppliers and retailers are integrated as a whole, from the whole. The optimal price and fresh-keeping input strategy are formulated to maximize the profit of the overall fresh agricultural product supply chain. Therefore, in the life cycle of fresh produce $[0, T]$, the total profit of the internal fresh produce supply chain is at the discount rate $\rho$. For discounting, the corresponding dynamic optimization problem is:

$$\max_{p(\cdot),\, u(\cdot)} \int_0^T e^{-\rho t}\left(\big(p(t) - c_0 - c_1 g(t)\big)\big(a - bp(t) + \theta g(t)\big) - \frac{\eta}{2}u^2(t)\right)dt \qquad s\cdot t\cdot \quad \dot{g}(t) = \lambda u(t) - \delta g(t), g(0) = g_0 \tag{7}$$

Solve the optimization problem of (7), and draw the following conclusions.

**Proposition 1.** *Under the centralized scenario, the optimal selling price and fresh-keeping input of suppliers and retailers in the fresh agricultural product supply chain are:*

$$p^C(g) = \frac{a + bc_0 + (\theta + bc_1)g}{2b} \tag{8}$$

$$u^C(g) = \frac{\lambda}{\eta}(2A_1 g + A_2) \tag{9}$$

In $A_1 = \frac{b\eta(\rho+2\delta)-\xi_1}{4b\lambda^2}$, $A_2 = \frac{\eta(a-bc_0)(\theta-bc_1)}{b\rho\eta+\xi_1}$, $\xi_1 = \sqrt{b\eta(b\eta(\rho+2\delta)^2 - 2\lambda^2(\theta-bc_1)^2)}$. In addition, the freshness time curve of fresh agricultural products is:

$$g^C(t) = g_T^C + \left(g_0 - g_T^C\right)e^{-R_1 t} \tag{10}$$

In $g_T^C = \frac{4b\eta\lambda^2(a-bc_0)(\theta-bc_1)}{(b\rho\eta+\xi_1)(\xi_1-b\eta(\rho-2\delta))}$, $R_1 = \frac{\xi_1^2-(b\eta(\rho-2\delta))^2}{4b\eta(\xi_1+b\eta(\rho-2\delta))} > 0$. $g_T^C$ for time $t$ when trending towards the fresh produce life $T$ cycle, stable or steady-state value of freshness of fresh produce under the concentration scenario.

**Prove:** The objective function of the supply chain of fresh agricultural products is: $J^* = e^{-\rho t}V^C(g)$. Among them, the optimal value function $V^C(g)$, based on the freshness evolution equation of fresh agricultural products, the HJB equation can be obtained as:

$$\rho V^C(G) = \max_{p,u}\left\{(p - c_0 - c_1 g)(a - bp + \theta g) - \frac{\eta}{2}u^2 + \frac{\partial V^C}{\partial g}(\lambda u - \delta g)\right\}$$

Sure $p$ and $u$ To maximize the right-hand side of the HJB equation, we get:

$$p = \frac{a + bc_0 + (\theta + bc_1)g}{2b} \tag{11}$$

$$u = \frac{\lambda}{\eta}\frac{\partial V^C}{\partial g} \tag{12}$$

Substituting the above Eqs. (11) and (12) into the right-hand side of the HJB equation, we get:

$$\begin{aligned}\rho V^C = {} & \frac{(\theta - bc_1)^2 g^2}{4b} - \frac{\left((a - bc_0)(\theta - bc_1)/2 + b\delta\left(\partial V^C/\partial g\right)\right)g}{b} \\ & + \frac{\eta(a - bc_0)^2 + 2b\lambda^2\left(\partial V^C/\partial g\right)^2}{4b\eta}\end{aligned} \tag{13}$$

Optimal value function $V^C$ is a quadratic function form because the optimal price and fresh-keeping input problem is a linear quadratic adjustment problem, so the optimal value function $V^C$ can be expressed as:

$$V^C(g) = A_1 g^2 + A_2 g + A_3 \tag{14}$$

From the above formula (14), it can be obtained that about $g$. The first derivative of is:

$$\frac{\partial V^C}{\partial g} = 2A_1 g + A_2 \tag{15}$$

Substitute the above Eqs. (14) and (15) into Eq. (13) to get:

$$\rho A_1 g^2 + \rho A_2 g + \rho A_3 = \frac{\left(4b\lambda^2 A_1^2 - 2\eta\left(2b\delta A_1 - (\theta - bc_1)^2/4\right)\right)g^2}{2b\eta} - \frac{\left(4bA_1A_2\lambda^2 - 2\eta\left(b\delta A_2 + (a - bc_0)(\theta - bc_1)/2\right)\right)g}{2b\eta} + \frac{b\lambda^2 A_2^2 + \eta\left((a - bc_0)^2/2\right)}{2b\eta} \tag{16}$$

Using the above formula (16) with the undetermined coefficient method, we can obtain $A_1$ and $A_2$ as well as $A_3$ expression, $A_3$. The expression is as follows:

$$A_3 = \frac{(a - bc_0)^2(\rho\Delta_1 - \xi_1)}{4b\rho\left(\rho\Delta_1 + \lambda^2\left(2b\theta c_1 - b^2c_1^2 - \theta^2\right) + \rho\xi_1\right)}.$$

In, $\Delta_1 = \eta\left((\rho + \delta)^2 + \delta^2\right)$.

According to the above formula, the total profit of the fresh agricultural product supply chain can be calculated as follows:

$$J^C = A_1 g_0^2 + A_2 g_0 + A_3 \tag{17}$$

Substitute (9) into (1) to obtain the differential equation for the optimal freshness of fresh agricultural products. Integrating this equation can get the curve of the freshness of agricultural products with time, as shown in the expression (10), where, in the life cycle of fresh agricultural products within, if and only if $R_1 > 0$. Freshness steady state value $g_T^C$ is globally stable, that is: $2b\eta(2b\eta\delta(\rho + \delta) - \lambda^2(\theta - bc_1)^2) > 0$.

It can be seen from proposition 1 that the sales price of fresh agricultural products $p(t)$ and fresh-keeping inputs $u(t)$. About freshness (state variable) $g(t)$ increases linearly, indicating that when the freshness of agricultural products is high, the decision makers of the operating enterprises will increase the sales price and increase the investment in freshness preservation to benefit from consumers' preference for high freshness agricultural products.

Will $g_T^C$ substitute into formulas (8) and (9) can be derived in the life cycle of fresh produce $[0, T]$ homeostasis selling price $p_T^C$ and fresh-keeping inputs $u_T^C$, that is:

$$p_T^C = \frac{a + bc_0 + (\theta + bc_1)g_T^C}{2b}, u_T^C = \frac{\lambda}{\eta}\left(A_1 g_T^C + A_2\right)$$

About $p_T^C$, $u_T^C$, $g_T^C$ important parameters in $(\lambda, \theta, c_1)$, the sensitivity analysis has the following conclusions.

**Corollary 1.** *$p_T^C$, $u_T^C$, $g_T^C$ with important parameters $\lambda$, $\theta$, $c_1$, there are the following relationships:* $\frac{\partial p_T^C}{\partial \lambda} > 0$, $\frac{\partial u_T^C}{\partial \lambda} > 0$, $\frac{\partial g_T^C}{\partial \lambda} > 0$, $\frac{\partial p_T^C}{\partial \theta} > 0$, $\frac{\partial u_T^C}{\partial \theta} > 0$, $\frac{\partial g_T^C}{\partial \theta} > 0$, $\frac{\partial p_T^C}{\partial c_1} < 0$, $\frac{\partial u_T^C}{\partial c_1} < 0$, $\frac{\partial g_T^C}{\partial c_1} < 0$.

From corollary 1, it can be concluded that in the life cycle of $[0, T]$ fresh agricultural products, homeostasis selling price, preservation inputs, and freshness vary with $\lambda$ and $\theta$ increases, and increases are positively correlated, following $c_1$ increase, and decrease is a negative correlation. When the freshness is put into the effective coefficient $\lambda$. When it is more significant, that is, when the contribution of fresh-keeping input to freshness is more outstanding, the decision-makers of suppliers are stimulated to invest more in fresh-keeping, resulting in the high freshness of agricultural products, so that decision-makers can formulate higher (compared to ordinary agricultural products) sales price. When parameter $\theta$ when is more extensive, it means that the freshness of agricultural products has a more effective contribution rate to the demand. It can inspire decision-makers to set higher freshness inputs and retail prices. However, when the parameter $c_1$ when is higher, when the operation inefficiency is high, the high fresh-keeping input will significantly increase the unit cost of fresh agricultural products. Therefore, the decision-makers of the operating enterprise will reduce the fresh-keeping input to reduce the cost of agricultural products.

Substitute Eq. (10) into Eqs. (8) and (9) to obtain the optimal sales price of fresh agricultural products and the time curve of suppliers' fresh-keeping investment, such as proposition 2.

**Proposition 2.** *Under the centralized scenario, the optimal sales price and preservation input time curve of suppliers and retailers in the fresh agricultural product supply chain are:*

$$p^C(t) = \frac{a + bc_0 + (\theta + bc_1)g_T^C}{2b} + \frac{\theta + bc_1}{2b}\left(g_0 - g_T^C\right)e^{-R_1 t} \tag{18}$$

$$u^C(t) = \frac{\lambda}{\eta}\left(2A_1 g_T^C + A_2\right) + \frac{\lambda}{\eta}2A_1\left(g_0 - g_T^C\right)e^{-R_1 t} \tag{19}$$

Equation (18) shows two pricing methods for decision-makers in fresh agricultural product supply chain operations: skimming pricing and penetration pricing (Yan et al., 2021; Lu et al., 2019). However, the pricing strategy chosen depends on the initial freshness value $g_0$ and steady-state freshness value $g_T^C$ relationship. When the initial freshness value is higher than the steady state freshness value, $g_0 > g_T^C$, the selling price of fresh agricultural products is monotonically decreasing, that is, skimming pricing. Instead, when $g_0 < g_T^C$, the sales price of fresh agricultural products increases monotonically and eventually reaches a fixed value in a steady state, that is, penetration pricing. The above results show that when the initial freshness of fresh agricultural products is large enough, the decision makers of the operating enterprise will set a high initial price (the price is higher than that of agricultural products with low initial freshness) to earn more profits, that is, the higher the initial freshness of agricultural products from the place of origin to the point of sale, the higher the price is, and the more profit is obtained. It can be seen from Eq. (10) that when $g_0 > g_T^C$ hour, $(g_0 - g_T^C)e^{-R_1 t}$ along with $R_1$. Therefore, the freshness of agricultural products continues to decrease with time, so the operating enterprises have to reduce the sales price, that is, sell at a lower price, however, when the initial freshness of fresh produce is low. $g_0 < g_T^C$ hour, producers or farmers provide agricultural products with low initial freshness. However, the operating company has carried out preservation treatment to make the agricultural products with low initial freshness fresher so that the freshness increases with the preservation treatment; therefore, fresh produce supply chain operators can increase retail prices accordingly.

In addition, the monotonicity of the optimal preservation input time curve is the same as the sales price. That is, when $g_0 > g_T^C$, the fresh-keeping input continuously decreases or decreases to a steady state with time. Otherwise, the fresh-keeping input increases to a steady state with time.

When the initial freshness of the product reaches a steady state, $g_0 = g_T^C$, the sales price is maintained, $p^C(t) = \frac{a+bc_0+(\theta+bc_1)g_T^C}{2b}$ constant and freshness input is maintained $u^C(t) = \frac{\lambda}{\eta}(2A_1 g_T^C + A_2)$, the constant does not change. It can be seen from Eq. (10) that the freshness of fresh agricultural products is maintained at $g_T^C$. The freshness level is equivalent to the optimal solution under static conditions without any processing of agricultural products.

Also, especially parameter $c_1$, the operational inefficiency coefficient pair $g_T^C$ has an extraordinary impact and essential impact on the pricing strategy of the operating enterprise, and its impact is as follows.

**Corollary 2.** *Due to the operational inefficiency, factor $c_1$ exists $0 < c_1 < \frac{\theta}{b}$. Within the range, the steady-state freshness of agricultural products must meet the* $0 < g_T^C < \frac{\theta\lambda^2(a-bc_0)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$.

1. *When $g_0 > \frac{\theta\lambda^2(a-bc_0)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$, the operational inefficiency coefficient is at any $c_1 \in (0, \frac{\theta}{b})$. In the range of values, fresh agricultural product supply chain operators choose the skimming pricing strategy.*
2. *When $0 < g_0 < \frac{\theta\lambda^2(a-bc_0)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$, there is a threshold $\tilde{c}_1$, this threshold enables a shift in pricing strategy, i.e., when $c_1 \in (0, \tilde{c}_1)$ fresh agricultural product supply chain operators adopt penetration pricing, when $c_1 \in (\tilde{c}_1, \frac{\theta}{b})$, the pricing strategy of fresh agricultural product supply chain operators has shifted from penetration pricing to skimming pricing, where the threshold $\tilde{c}_1$ satisfy $g_0 = \frac{\lambda^2(a-bc_0)(\theta-b\tilde{c}_1)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$.*

**Proof.** From proposition 2, we know that the monotonicity of the sales price of fresh agricultural products depends on the initial value $g_0$ and steady state value $g_T^C$ relationship between the two, where $R_1 > 0$. When $g_0 > g_T^C$, $(g_0 - g_T^C)e^{-R_1 t}$ along with $R_1$ increase and decrease continuously, and the sales price is monotonically decreasing with time, that is, the enterprise adopts the skimming pricing strategy; when $g_0 < g_T^C$ the sales price increases concerning time, that is, the enterprise adopts the penetration pricing strategy.

To ensure $g_T^C > 0$, operational inefficiency factor $c_1$ should satisfy $0 < c_1 < \frac{\theta}{b}$, it follows that, $0 < g_T^C < \frac{\theta\lambda^2(a-bc_0)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$.

Therefore, when $g_0 > \frac{\lambda^2(a-bc_0)(\theta-b\tilde{c}_1)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$ hour, $g_0 > g_T^C$, that is, the initial freshness value is greater than the freshness value in the steady state, and the operating company will choose the skimming pricing strategy.

However, when $g_0 < \frac{\lambda^2(a-bc_0)(\theta-b\tilde{c}_1)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$, there is a threshold $\tilde{c}_1$ satisfy $g_0 = \frac{\lambda^2(a-bc_0)(\theta-b\tilde{c}_1)}{2b\eta(2b\eta\delta(\rho+\delta)-\lambda^2\theta^2)}$.

When operational inefficiency factor $c_1$ less than threshold $\tilde{c}_1$, which is $0 < c_1 < \tilde{c}_1$ hour, $g_0 > g_T^C$, fresh agricultural product supply chain operators will choose skimming pricing; when the operating inefficiency coefficient $c_1$ greater than the threshold $\tilde{c}_1$ and less than the upper limit of the interval $\frac{\theta}{b}$ which is $\tilde{c}_1 < c_1 < \frac{\theta}{b}$ hour, $g_0 < g_T^C$, operating companies will choose penetration pricing.

From corollary 2, it can be concluded that the operational inefficiency coefficient $c_1$. Different values will lead companies to choose different pricing strategies. When the initial value of freshness of agricultural products is considerable, $c_1$ exists $0 < c_1 < \frac{\theta}{b}$. Scope changes impact pricing strategy changes, regardless of how $c_1$ changes. Operating businesses always adopt a skimming pricing strategy. However, when the initial value of freshness of agricultural products is small, with the operation inefficiency coefficient $c_1$. As the value increases, the operating enterprise adopts penetration pricing at first (after simple freshness treatment reaches a particular freshness value) and then adopts skimming pricing (as the freshness decreases), indicates the high operational inefficiency of the operating enterprise (the coefficient of operational inefficiency is $c_1$ large). This leads to low investment in preservation and freshness and low sales prices. In addition, the higher the initial freshness, the higher the switching threshold of the pricing strategy of fresh agricultural product supply chain operators. $\tilde{c}_1$ smaller (limited switching) indicates a lower operational inefficiency when the initial freshness of produce is higher (operational inefficiency coefficient is $c_1$ small). It can change the pricing strategy of the operating company. Therefore, in this scenario, the company will consider the direct impact of operational inefficiency in pricing; that is, the operating company's pricing strategy is $c_1$ more sensitive.

### *3.3.1. Equilibrium strategies in decentralized scenarios*

First, it is assumed that fresh produce suppliers and retailers are rational and aim to maximize their profits. According to the dynamic equations of (1, 5), and (6), the fresh produce supply chain operating companies are considered to discount $\rho$ at a discount rate during the fresh produce life cycle $[0, T]$. Therefore, the corresponding optimization problems at this time are:

$$
\begin{aligned}
&\max_{w(\cdot),u(\cdot)} \int_0^T e^{-\rho t}\left(\big(w(t) - c_{s0} - c_1 g(t)\big)\big(a - bp(t) + \theta g(t)\big) - \frac{\eta}{2}u^2(t)\right)dt \\
&\max_{p(\cdot)} \int_0^T e^{-\rho t}\Big(\big(p(t) - w(t) - (c_0 - c_{s0})\big)\big(a - bp(t) + \theta g(t)\big)\Big)dt \qquad (20) \\
&\quad s\cdot t\cdot \qquad \dot{g}(t) = \lambda u(t) - \delta g(t), g(0) = g_0
\end{aligned}
$$

Equation (20) is a differential game model involving two players (fresh agricultural product supply chain and retailer), which includes three control variables, the sales price $p(t)$, wholesale prices $w(t)$, supplier fresh-keeping input $u(t)$ and a state variable called freshness $\dot{g}(t)$.

In (20), the model in the formula is the Stackelberg differential game model. Among them, fresh produce suppliers play a leading role in the supply chain, while retailers play a corresponding role as followers. The order of the game between the two is as follows: the supplier first announces the wholesale price of fresh agricultural products $w(t)$ and fresh-keeping inputs $u(t)$. The retailer then determines the fresh produce sales price $p(t)$. Using the reverse induction method, the decision-making problem of fresh agricultural product retailers is solved first, and then the decision-making problems of fresh agricultural product suppliers are solved.

The following conclusions are drawn about the equilibrium strategies of fresh produce retailers and suppliers.

**Proposition 3.** *Under the decentralized scenario, the equilibrium fresh agricultural product sales price, the wholesale price, and fresh-keeping input are:*

$$p^D(g) = \frac{3a + b(c_0 + c_{r0}) + (3\theta + bc_1)g}{4b} \tag{21}$$

$$w^D(g) = \frac{a + bc_{s0} + (\theta + bc_1)g}{2b} \tag{22}$$

$$u^D(g) = \frac{\lambda}{\eta}(2B_1 g + B_2) \tag{23}$$

In $B_1 = \frac{b\eta(\rho+2\delta)-\xi_2}{4b\lambda^2}$, $B_2 = \frac{\eta(a-bc_0)(\theta-bc_1)}{2(b\rho\eta+\xi_2)}$, $\xi_2 = \sqrt{b\eta(b\eta(\rho+2\delta)^2 - \lambda^2(\theta-bc_1)^2)}$. In addition, the freshness time curve of fresh agricultural products is:

$$g^D(t) = g_T^D + \left(g_0 - g_T^D\right)e^{-R_2 t} \tag{24}$$

In $g_T^D = \frac{2b\eta\lambda^2(a-b(c_0+c_{r0}))(\theta-bc_1)}{(b\rho\eta+\xi_2)(\xi_2-b\eta(\rho-6\delta))}$, $R_2 = \frac{\xi_2^2-(b\eta(\rho-6\delta))^2}{8b\eta(\xi_2+b\eta(\rho-6\delta))} > 0$. $g_T^D$ is time $t$ when trending towards the fresh produce life $T$ cycle.

**Prove:** The objective functions of fresh produce suppliers and retailers are: $J_S^* = e^{-\rho t}V_S^D(g)$, $J_R^* = e^{-\rho t}V_R^D(g)$. Among them, $V_S^D(g)$ and $V_R^D(g)$ representing the optimal value function of fresh agricultural product suppliers and retailers, first solve the retailer's pricing problem, and based on the freshness evolution equation of fresh agricultural products, the HJB equation can be obtained as:

$$\rho V_R^D = \max_p \left\{ (p - w - (c_0 - c_{s0}))(a - bp + \theta g) + \frac{\partial V_R^D}{\partial g}(\lambda u - \delta g) \right\} \tag{25}$$

Retailers aim to maximize profits, but the solution $p$ is the selling price that maximizes the profit, so the response function of the fresh agricultural product retailer can be obtained as follows:

$$p = \frac{a + b(w + (c_0 - c_{s0})) + \theta g}{2b} \tag{26}$$

Based on the retailer's (26) reaction function, the HJB equation for the fresh produce supplier is:

$$\rho V_S^D = \max_{w,u}\left\{(w - c_{s0} - c_1 g)(a - bp + \theta g) - \frac{\eta}{2}u^2 + \frac{\partial V_S^D}{\partial g}(\lambda u - \delta g)\right\} \tag{27}$$

The supplier's goal is to maximize profits, so solve the right-hand side of (27) $w$ and $u$, available:

$$w = \frac{a + bc_{s0} + (\theta + bc_1)g}{2b} \tag{28}$$

$$u = \frac{\lambda}{\eta}\frac{\partial V_S^D}{\partial g} \tag{29}$$

Substitute the above formula (28) into the formula (26) to get:

$$p = \frac{3a + b(2c_0 - c_{s0}) + (3\theta + bc_1)g}{4b} \tag{30}$$

Substitute the above Eqs. (28)–(30) into the HJB Eqs. (25) and (27) of the supplier and retailer, and assume that the quadratic, $V_S^D$, $V_R^D$ the optimal value function is:

$$\begin{aligned} V_S^D &= B_1 g^2 + B_2 g + B_3 \\ V_R^D &= E_1 g^2 + E_2 g + E_3 \end{aligned} \tag{31}$$

The six riccati equations are solved using the undetermined coefficient method, and the corresponding six parameters are obtained. $B_i, E_i, i = 1, 2, 3,$ among them, the parameters $B_1$ and $B_2$ have been given in proposition 3.3, and the other four parameters are as follows:

$$B_3 = \frac{2\rho(a - bc_0)(a - bc_{s0})\xi_2 + 2b\left(\left(bc_{r0}^2/2\right)\lambda^2(\theta - bc_1)^2 + \Delta_4\right)}{16b\rho(b\rho\eta + \xi_2)^2},$$

$$E_1 = \frac{\eta(\theta - bc_1)^2}{16\xi_2},$$

$$E_2 = \frac{\eta(\theta - bc_1)\Delta_5}{16b\xi_2(\xi_2 + b\eta\rho)},$$

$$E_3 = \frac{\Delta_6 + \Delta_7 + \Delta_8}{32b\rho\xi_2(b\rho\eta + \xi_2)}.$$

In $\Delta_4 = a^2\eta((\rho+\delta)^2+\delta^2) + b\eta(bc_{s0}(c_0 - c_{s0}/2) - ac_0)((\rho+2\delta)^2+\delta^2)$, $\Delta_5 = \xi_2(a-b(c_0+c_{r0})) + (1/2b\eta\rho + 2\xi_2)(\eta(a-b(c_0+c_{r0}))(\lambda(\theta-bc_1))^2)$, $\Delta_6 = (a-b(c_0+c_{r0}))^2((1/2b^2)(b\eta(\rho+2\delta)-\xi_2)^2 + \eta^2(\rho+2\delta)(\rho+\delta))$, $\Delta_7 = (1/2b)(a-b(c_0+c_{r0}))(b\eta(\rho+2\delta)-\xi_2)((1/2(b\eta\rho+\xi_2))(\lambda(\theta-bc_1))^2\ (4\eta(a-b(c_0+c_{r0})))+\eta(a-b(c_0+c_{r0}))(3\rho+4\delta))$, $\Delta_8 = \frac{(\eta(a-bc_0))^2(\lambda(\theta-bc_1))^4}{2(b\eta\rho+\xi_2)^2} + \frac{(\eta\lambda(\theta-bc_1))^2(a-b(c_0+c_{r0}))(a-bc_0)(\rho+2\delta)}{2(b\eta\rho+\xi_2)}$.

The profits of fresh agricultural product suppliers, retailers, and the overall supply chain are as follows:

$$J_S^D = B_1 g_0^2 + B_2 g_0 + B_3 \tag{32}$$

$$J_R^D = E_1 g_0^2 + E_2 g_0 + E_3 \tag{33}$$

$$J^D = J_S^D + J_R^D = (B_1+E_1)g_0^2 + (B_2+E_2)g_0 + B_3 + E_3 \tag{34}$$

Similarly, the time curve of the freshness of fresh agricultural products is shown in the expression (24), where the life cycle of fresh agricultural products is $[0,T]$, if and only if $R_2 > 0$, the steady state value of freshness $g_T^C$ is globally stable, that is, the parameters satisfy: $b\eta(8b\delta\eta\rho - \lambda^2(\theta-bc_1)^2) > 0$.

It can be clearly seen from proposition 3 that in the life cycle of fresh agricultural products $[0,T]$ inside, balance the selling price of fresh agricultural products $p(t)$, wholesale prices $w(t)$ and fresh-keeping inputs $u(t)$, it's all about freshness (state variables) $g(t)$, it is a linear increase, indicating that the higher the freshness of agricultural products, the more motivated suppliers to increase their investment in fresh-keeping, and set higher wholesale prices so that retailers also set higher retail prices.

However, in the life cycle of fresh produce $[0,T]$ inside, for any fresh produce freshness $g$, $(P^D(g))' = \frac{3\theta+bc_1}{4b}$, $(w^D(g))' = \frac{\theta+bc_1}{2b}$, $(P^D(g))' > (w^D(g))' > 0$ establishment of the capital, it shows that the impact of freshness on sales price and wholesale price is more significant than that of the latter. This is because the freshness of fresh agricultural products has a positive (first-order derivative greater than 0) impact on the sales price and wholesale price. The wholesale price of agricultural products also positively impacts the sales price (as shown by the expression (3–26). Therefore, retail prices are doubly affected by the freshness of fresh produce: on the one hand, freshness $g$ on sale price $p$ has a direct impact; on the other hand, freshness $g$ by affecting wholesale prices $w$ to influence the selling price $p$.

Same, will $g_T^D$ substitute into (21–23), it can be concluded that in the life cycle of fresh agricultural products $[0,T]$ homeostasis equilibrium selling price $P_T^D$, wholesale prices, fresh-keeping input $u_T^D$, which is about the essential parameters ($\lambda$, $\theta$, $c_{s0}$, $c_{r0}$, $c_1$). The sensitivity analysis of, indicates steady-state fresh agricultural product sales prices, fresh-keeping inputs, freshness with $\lambda$ and $\theta$ increases and increases are positively correlated, $c_{s0}$, $c_{r0}$, $c_1$ increase and decrease is a negative correlation. This conclusion is similar that in the concentration scenario.

Substitute (24) into (21, 22), and (23), we can get the life cycle of fresh agricultural products $[0,T]$. The time curve of the internal equilibrium selling price, wholesale price, and fresh-keeping input is as follows.

**Proposition 4.** *The equilibrium fresh agricultural product sales price, the wholesale price, and fresh-keeping input under the decentralized scenario are:*

$$p^D(t) = \frac{3a + b(2c_0 - c_{s0}) + (3\theta + bc_1)g_T^D}{4b} + \frac{3\theta + bc_1}{4b}\left(g_0 - g_T^D\right)e^{-R_2 t} \tag{35}$$

$$w^D(t) = \frac{a + bc_{s0} + (\theta + bc_1)g_T^D}{2b} + \frac{\theta + bc_1}{2b}\left(g_0 - g_T^D\right)e^{-R_2 t} \tag{36}$$

$$u^D(t) = \frac{\lambda}{\eta}\left(2B_1 g_T^D + B_2\right) + \frac{\lambda}{\eta}2B_1\left(g_0 - g_T^D\right)e^{-R_2 t} \tag{37}$$

In a similar concentration scenario, fresh produce suppliers and retailer decision-makers face two pricing strategies: skimming and penetration pricing (Lu et al., 2019). Furthermore, any choice pricing strategy relies on the initial produce freshness value $g_0$ and steady-state produce freshness value $g_T^D$ relationship between the two. When the initial produce freshness value $g_0$ when is higher, the operational inefficiency of the supplier does not affect the pricing strategy of agricultural product sales, that is, if the initial agricultural product freshness value $g_0$ is high, the freshness investment of suppliers does not improve the freshness of agricultural products, but increases the marginal cost of agricultural products, but the freshness will naturally decline with time. For this fresh agricultural product, suppliers and retailers choose skimming pricing. However, when the initial produce freshness value $g_0$ when lower, there is a threshold (the threshold of operational inefficiency that can cause a shift in pricing strategy). Fresh produce suppliers and retailers choose penetration pricing when it is less than this threshold. When it is more significant than this threshold, fresh produce suppliers and retailers choose to skim pricing.

## 4. Equilibrium comparison between two scenarios

This section compares the steady-state fresh agricultural product sales price, freshness, preservation input, and channel profit under the two scenarios and draws the following conclusions.

**Inference 3** The steady-state fresh agricultural product sales prices in the two scenarios have the following relationships:

1. when $\frac{\lambda^2\theta(\theta - bc_1)}{\eta} < b\delta(\rho - 2\delta)$ time, then $p_T^D > p_T^C$.
2. when $\frac{\lambda^2\theta(\theta - bc_1)}{\eta} = b\delta(\rho - 2\delta)$ time, then $p_T^D = p_T^C$.
3. when $\frac{\lambda^2\theta(\theta - bc_1)}{\eta} > b\delta(\rho - 2\delta)$ time, then $p_T^D < p_T^C$.

Definition $\zeta = \frac{\lambda^2\theta(\theta - bc_1)}{\eta}$ for the effectiveness of fresh-keeping, the benefits of fresh-keeping inputs (the benefits that suppliers' fresh-keeping inputs bring to enterprises operating in the supply chain of fresh agricultural products). Inference 3 shows that when the preservation effectiveness is below or below a certain threshold $(b\delta(\rho - 2\delta))$hour, the optimal selling price of fresh agricultural products under the centralized scenario is lower or lower than the selling price under the decentralized scenario, mainly due to the double marginal effect. However, when the preservation effectiveness is above or more significant than this threshold, the high freshness of agricultural products attracts and expands the market demand of consumers, resulting in high prices. As a result, the sales price of fresh agricultural products in the complete scenario is higher than that in the decentralized scenario. This scenario will likely arise when consumers strongly desire to buy (and are willing to pay for) high-freshness produce. The results reflect when fresh produce life cycle $[0, T]$, when there are dynamic pricing (sales price and wholesale price) and non-pricing decision variables (preservation input), the 'double marginal effect' does not necessarily lead to high prices for fresh produce.

The following conclusions can be drawn by comparing the preservation input and freshness channel profit under the two scenarios.

**Inference 4.** Under the two scenarios, the steady-state fresh agricultural product preservation input, freshness, and channel profit have the following relationship: $u_T^C > u_T^D$, $g_T^C > g_T^D$, $J^C > J^D$.

It can be seen from inference 4 that the input, freshness overall profit of the supply chain, that is, the channel profit, are higher than the corresponding equilibrium in the decentralized scenario under the centralized scenario. The dispersion scenario leads to a double marginal effect, triggering channel conflict. However, this problem does not arise in the centralized scenario since all decisions are made from a profit maximization perspective of the overall supply chain (suppliers and retailers combined, two parts of an organization).

## 5. Coordination of supply chain of fresh agricultural products two-part tariffs contract

According to the equilibrium comparison of the above two scenarios, it is found that the decentralized scenario leads to a low overall profit of the supply chain, which has inspired some scholars to discuss such a question: how to coordinate the dynamic fresh agricultural product supply chain to make the overall profit reach the overall profit level under the centralized scenario. When fresh produce suppliers decide wholesale prices and retailers decide retail prices, scholars such as Bhardwaj and Balasubramanian (2005), Jeuland and Shugan (2008), and Inderst and Shaffer (2019) found that suppliers can coordinate the supply chain through two wholesale prices, that is, two pricing contracts. This section also selects a two-part pricing contract (TPTC). It uses this contract to test whether it can also coordinate the dynamic fresh agricultural product supply chain, assuming that the fresh agricultural product wholesale price is:

$$w(g) = c_{s0} + c_1 g + \frac{k}{D} \tag{38}$$

In $k > 0$ is a positive constant. It can be seen from (38) that this transfer price is determined by fixed costs $c_{s0}$ and variable costs $c_1 g + \frac{k}{D}$ composition, while the variable cost depends on the freshness state variable $g$.

Substitute (38) into (5) and (6) to obtain the profits of suppliers and retailers, namely channel members, which are:

$$J_S = \int_0^T e^{-\rho t}\left(k - \frac{\eta}{2}u^2(t)\right)dt \tag{39}$$

$$J_R = \int_0^T e^{-\rho t}\left(\left(p(t) - c_o - c_1 g\right)\left(a - bp(t) + \theta g(t)\right) - k\right)dt \tag{40}$$

It can be seen from the above formula that $k$ plays a role in profit sharing in the profit of channel members. In order to achieve the profit in the entire scenario, the retailer provides two pricing contracts, and the situation is as follows: fresh produce suppliers at marginal cost $c_{s0} + c_1 g$ price (cost price) sold to retailers, and charge retailers per unit of produce at the end of the selling season $k$ fixed fee. $k$ ability to distribute profits between fresh produce suppliers and retailers. However, $k$ profit distribution can achieve the same effect as a revenue-sharing contract (Lu et al., 2019; Phouratsamaya et al., 2021).

Under this coordination mechanism, the fresh produce supplier is the leader or master of the Stackelberg game. First, the supplier announces the wholesale $w$ price for $c_{s0} + c_1 g + \frac{k}{D}$, which is $(c_{s0}, c_1, k)$, and decides on fresh-keeping investment to maximize the profit of the overall supply chain of fresh agricultural products; second, retailers, as followers or followers, determine retail price $p$ to maximize self-interest. Through the reverse solution method, first, solve the problem of fresh agricultural product retailers, that is, to decide the retail price, and then solve the equilibrium wholesale price and fresh-keeping input of fresh agricultural product suppliers. The following conclusions can be drawn.

**Proposition 5.** *The supplier uses two pricing contracts to coordinate the supply chain of fresh agricultural products, so that the profit in the decentralized scenario can reach the optimal profit in the centralized scenario.*

**Proof.** Let $V_S^T$ and $V_R^T$ represent the optimal value function of fresh produce suppliers and retailers, the retailer's HJB equation is:

$$\rho V_R^T = \max_p \left( (p - c_o - c_1 g)(a - bp + \theta g) - k + \frac{\partial V_R^T}{\partial g}(\lambda u - \delta g) \right) \tag{41}$$

The retailer's goal is to maximize profit, but solving the right-hand side of the maximization Eq. (41) yields the equilibrium price as:

$$p^T = \frac{a + bc_0 + (\theta + bc_1)g}{2b} \tag{42}$$

Based on the dynamic evolution equation of freshness of fresh agricultural products such as formula (1), the maximization problem of fresh agricultural products suppliers is:

$$\max_{u}\int_{0}^{T}e^{-\rho t}\left((p-c_0-c_1g)(a-bp+\theta g)-\frac{\eta}{2}u^2\right)dt \tag{43}$$

Its corresponding HJB equation is:

$$\rho V_S^T=\max_{u}\left\{(p-c_{s0}-c_1g)(a-bp+\theta g)-\frac{\eta}{2}u^2+\frac{\partial V_S^T}{\partial g}(\lambda u-\delta g)\right\} \tag{44}$$

Substitute (42) into (44) and maximize the right-hand side of (44) to get:

$$u_S^T=\frac{\lambda}{\eta}\frac{\partial V_S^T}{\partial g} \tag{45}$$

However, the quadratic optimal value function $V_S^T,\ V_R^T$ can be expressed as:

$$\begin{aligned}V_S^T&=F_1g^2+F_2g+F_3\\ V_R^T&=I_1g^2+I_2g+I_3\end{aligned} \tag{46}$$

Similarly, it can be concluded that: $F_1=A_1,\ F_2=A_2,\ F_3=A_3$,

$$I_1=\frac{\eta(\theta-bc_1)^2}{4\xi_1},$$

$$I_2=\frac{b\eta^2(\theta-bc_1)\left(\Delta_9+a\theta\lambda^2(\theta+2bc_1)\right)}{\xi_1(b\rho\eta+\xi_1)^2},$$

$$I_3(k)=\frac{3b^4(\Delta_{10}+\Delta_{11}+\Delta_{12})+\Delta_{13}+\Delta_{14}-b^2(\Delta_{15}+\Delta_{16})-\Delta_{17}-\Delta_{18}-\Delta_{19}-\Delta_{20}}{2\rho\xi_1(b\rho\eta+\xi_1)^3}-\frac{(\Delta_{21}+\Delta_{22})b\eta^2k}{2\rho\xi_1(b\rho\eta+\xi_1)^3}.$$

In
$\Delta_9=b(c_0+c_{r0})\lambda^2(\theta-bc_1)^2+(a-bc_0)(b\eta(\rho+2\delta)^2+\rho\xi_1)$,
$\Delta_{10}=12(4\theta-bc_1)\lambda^4\theta^2c_1^2c_{r0}^2$,
$\Delta_{11}=2\eta(\rho+2\delta)^2(c_0^2((\rho+\delta)^2-\rho\delta)-\lambda^2cc_{s0}(ac_1+2\theta c_0))$,
$\Delta_{12}=2c_1\eta\lambda^2c_0\left(\theta c_0\left((\rho+4\delta)^2+4\rho^2\right)-4ac_1\left((\rho+\delta)^2-\rho\delta\right)\right)$,
$\Delta_{13}=2ab\eta\left(a(\rho+2\delta)^2\left((\rho+\delta)^2-\rho\delta\right)+\theta\rho^2\lambda^2(3ac_1+\theta(4c_0-c_{s0}))\right)$,
$\Delta_{14}=3b\theta c_{r0}\lambda^2\left(2ab\eta\delta(\rho+\delta)-2\lambda^2\theta c_{r0}-\eta\theta a^2\rho^2\right)$,
$\Delta_{15}=2\eta(\rho+2\delta)^2\left(2ac_0\eta\left((\rho+\delta)^2-\rho\delta\right)-\lambda^2\theta c_1c_{s0}(1+2a\theta)\right)$,
$\Delta_{16}=\lambda^2\left(\theta^2\left(\eta c_0\left((\rho+4\delta)^2+4\rho^2\right)+8c_1\lambda^2\theta c_{r0}^2\right)+ac_1\eta\left(16c_0\theta\left((\rho+\delta)^2-\rho\delta\right)+3ac_1\rho^2\right)\right)$,
$\Delta_{17}=\lambda^2\theta(\theta-2bc_1)(a-(3c_0-2c_{s0}))$,
$\Delta_{18}=b^2\left(a\lambda^2c_1^2-2\eta(a-c_0)\left((\rho+2\delta)^2-\delta(\rho+\delta)\right)-b\lambda^2c_1^2(3c_0-2c_{s0})\right)$,
$\Delta_{19}=2(4\theta-bc_1)b^5c_1^3\lambda^4c_{r0}^2$,

$\Delta_{20} = b^5 c_1^2 \lambda^2 \eta \left( c_0 \left( (\rho + 4\delta)^2 + 4\rho^2 \right) + c_0 \rho^2 (5c_0 - 2c_{s0}) \right),$
$\Delta_{21} = 4\rho\xi_1 \left( 2\eta b^2 \left( (\rho + 2\delta)^2 - \delta(\rho + \delta) \right) - 3b\lambda^2 (\theta - bc_1)^2 \right),$
$\Delta_{22} = 4b\lambda^2 \left( \lambda^2 (\theta - bc_1)^4 - b\eta\theta(\theta - 2bc_1) \left( (\rho + 4\delta)^2 + 4\rho^2 \right) - 2\eta c_1^2 b^3 \left( (\rho + 2\delta)^2 + (3/2)\rho^2 \right) \right).$

Therefore, $p^T = p^C,\ g^T = g^C,\ u^T = u^C,$ the equilibrium strategy is equivalent to the concentration scenario.

Similarly, the profits of fresh produce suppliers and retailers are shown in Eqs. (47) and (48), and the coefficients are:

$$L_1 = A_1 - I_1 = -\frac{\eta\left( (\rho + 2\delta)(b\eta(\rho + 2\delta) - \xi_1) - \lambda^2 (\theta - bc_1)^2 \right)}{4\lambda^2 \xi_1},$$

$$L_2 = A_2 - I_2 = \frac{b\eta^2 (\theta - bc_1)(3a - b(4c_0 - c_{s0}))\lambda^2 (\theta - bc_1)^2}{\xi_1 (b\rho\eta + \xi_1)^2} - \frac{b\eta^2 (\theta - bc_1) 2\rho\xi_1 (a - bc_0) + 2b\eta\left( bc_0 - 2a\theta\lambda^2 \right)(\rho + 2\delta)^2}{\xi_1 (b\rho\eta + \xi_1)^2},$$

$L_3(k) = A_3 - I_3(k) = \Delta + \frac{(\Delta_{21} + \Delta_{22}) b\eta^2 k}{2\rho\xi_1 (b\rho\eta + \xi_1)^3},$ the expression $\Delta$ is omitted here due to its $\Delta$ complexity.

However, Zaccour (2008) and Zhang et al. (2016) scholars pointed out that an exogenous two-part pricing contract cannot coordinate the supply chain under the nash game and stackelberg game. Lambertini,(2014), Tan et al. (2021), and Scholars from Kumar et al. (2021) found that when two pricing contracts use some endogenous function forms (which differ from exogenous forms), they can coordinate the supply chain. Therefore, Liu et al. (2021c) pointed out that in order to coordinate the supply chain, it is necessary to make the steady-state equilibrium under the decentralized scenario reach the equilibrium level under the centralized scenario, that is, the equilibrium level under the decentralized scenario is equal to the equilibrium level under the centralized scenario. This paper is different from theirs. This model assumes that in addition to setting the wholesale price of fresh agricultural products, the supplier also decides other non-price variables (the input of agricultural products preservation) to maximize the profit of the overall supply chain.

In contrast, the retailer decides the selling price of fresh agricultural products to maximize the profit of the whole supply chain. To maximize their profits, that is, suppliers aim at maximizing overall profits, while retailers aim to maximize their profits. Based on this model structure, when two-part pricing is defined as a function of the freshness of fresh produce, it can satisfactorily coordinate the supply chain at each point in time during the fresh produce life cycle $[0, T]$, not just at a steady state.

Therefore, the equilibrium price and fresh-keeping input in this coordination scenario are equal to those in the centralized scenario, namely $p^T(t) = p^C(t),\ u^T(t) = u^C(t)$. The equilibrium price and fresh-keeping input under the coordination scenario are consistent with the conclusion of corollary 1. In the life cycle of fresh agricultural products $[0, T]$, homeostasis selling price, preservation inputs, and freshness vary with $\lambda$ and $\theta$ increases and increases are positively correlated, following $c_1$ increase and decrease is a negative correlation.

However, the equilibrium profits of fresh produce suppliers and retailers are:

$$J_S^T(k) = L_1 g_0^2 + L_2 g_0 + L_3(k) \tag{47}$$

$$J_R^T(k) = I_1 g_0^2 + I_2 g_0 + I_3(k) \tag{48}$$

The total profit of the fresh agricultural product supply chain under the coordination scenario is $J^T = J_S^T(k) + J_R^T(k) = J^C$, which is independent of the parameter. Total profit and $k$. It does not matter. However, the profits of fresh produce suppliers and retailers alike depend on, that is, two-channel members (operating companies) pass the parameter $k$ share the total profit of the fresh agricultural product supply chain. Therefore, an interesting question arises: how to set a suitable $k$ to distribute the profits of the fresh produce supply chain. Discuss next $k$ the problem. Only channel members are willing to participate in this game only when operating firms' profits are higher than those in the decentralized scenario. Then the parameters $k$ should satisfy:

$$\Delta J_S = J_S^T(k) - J_S^D = \frac{b\eta^2(\Delta_{21} + \Delta_{22})(k - k_1)}{2\rho\xi_1(b\rho\eta + \xi_1)^3} > 0 \tag{49}$$

$$\Delta J_R = J_R^T(k) - J_R^D = \frac{b\eta^2(\Delta_{21} + \Delta_{22})(k_2 - k)}{2\rho\xi_1(b\rho\eta + \xi_1)^3} > 0 \tag{50}$$

In $k_1 = \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_S^D - J_S^T(0))}{b\eta^2(\Delta_{21}+\Delta_{22})}$, $k_2 = \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_R^T(0) - J_R^D)}{b\eta^2(\Delta_{21}+\Delta_{22})}$, $\Delta J_S$ and $\Delta J_R$ are the additional profit for fresh produce suppliers and retailers under two pricing contracts. Nevertheless, satisfied $\Delta J_S + \Delta J_R = \Delta J_{S+R}$. Therefore, $k$ is more significant. The greater the additional profit shared by the suppliers of fresh agricultural products, the greater the $\Delta J_S = J_S^T(k) - J_S^D = \frac{b\eta^2(\Delta_{21}+\Delta_{22})(k-k_1)}{2\rho\xi_1(b\rho\eta+\xi_1)^3} > 0$ is more prominent, and vice versa.

The following conclusions are drawn regarding the feasible areas of the two pricing contracts in the supply chain of fresh agricultural products.

**Proposition 6.** *When $k_1 < k < k_2$ hour, fresh produce suppliers and retailers are willing to fulfill two pricing contracts, namely:*

$$c_{s0} + c_1 g^T + \frac{k_1}{a - bp^T + \theta g^T} < w^T < c_{s0} + c_1 g^T + \frac{k_2}{a - bp^T + \theta g^T}.$$

**Proof. According to formula (49), we can get:**

$$L_1 g_0^2 + L_2 g_0 + L_3(k) - B_1 g_0^2 - B_2 g_0 - B_3 > 0,$$

That is:

$$\frac{b\eta^2 k(\Delta_{21}+\Delta_{22})}{2\rho\xi_1(b\rho\eta+\xi_1)^3} > -\left(L_1 g_0^2 + L_2 g_0 + \Delta\right) + B_1 g_0^2 + B_2 g_0 + B_3 = J_S^T(k) - J_S^D,$$

Therefore, $k$ satisfy $k > \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_S^D - J_S^T(0))}{b\eta^2(\Delta_{21}+\Delta_{22})}$. Similarly, according to formula (50), we can get $k < \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_R^T(0) - J_R^D)}{b\eta^2(\Delta_{21}+\Delta_{22})}$.

However, let $k_1 = \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_S^D - J_S^T(0))}{b\eta^2(\Delta_{21}+\Delta_{22})}$, $k_2 = \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_R^T(0) - J_R^D)}{b\eta^2(\Delta_{21}+\Delta_{22})}$, simpler verification $J_S^T(0) < 0$, $J_R^D > 0$, therefore, $k_1 > 0$ and

$$\begin{aligned} k_2 - k_1 &= J_S^T(0) + J_R^T(0) - J_S^D - J_R^D \\ &= J^T - J^D > 0 \end{aligned}.$$

However, $k$ should satisfy $\frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_S^D - J_S^T(0))}{b\eta^2(\Delta_{21}+\Delta_{22})} < k < \frac{2\rho\xi_1(b\rho\eta+\xi_1)^3(J_R^T(0) - J_R^D)}{b\eta^2(\Delta_{21}+\Delta_{22})}$.

According to the above analysis, the contract form in proposition 6 can satisfactorily coordinate the supply chain and make fresh produce suppliers and retailers willing to accept this contract. In particular, suppliers can adjust wholesale prices by $w$, which is $c_{s0} + c_1 g + k$ very flexible and convenient distribution of profits.

However, when there is no more information or information asymmetry, it is impossible to accurately obtain the wholesale price value (Lau, 2008; Zhang et al., 2016). The Nash negotiation model effectively solves this problem (Nagarajan & Bassok, 2008). Choose the method proposed by Xie and Wei (2009), and Zhang et al. (2016): manufacturers or suppliers, and retailers have different preferences for extra profit (the value of extra profit that each channel member is willing to accept), the utility function of each channel member represents this preference. Assume that the utility functions of fresh produce suppliers and retailers are $u_s(\Delta J_s) = (\Delta J_s)^{\varsigma_s}$ and $u_r(\Delta J_R) = (\Delta J_R)^{\varsigma_r}$, in $\varsigma_s$ and $\varsigma_r$, representing the risk appetite coefficient of fresh produce suppliers and retailers. The more significant the coefficient, the more risk-averse the operating company is. However, the Nash negotiation model is as follows, that is, the optimization problem is:

$$\begin{aligned} &\max_{\Delta J_s, \Delta J_R} u_s(\Delta J_s) u_r(\Delta J_R) = (\Delta J_s)^{\varsigma_s}(\Delta J_R)^{\varsigma_r} \\ &s.t. \quad \Delta J_S + \Delta J_R = \Delta J_{S+R}, \Delta J_s > 0, \Delta J_R > 0 \end{aligned} \tag{51}$$

Equation (51) is $\Delta J_S = \frac{\varsigma_s}{\varsigma_s+\varsigma_r}\Delta J_{S+R}$ and $\Delta J_R = \frac{\varsigma_r}{\varsigma_s+\varsigma_r}\Delta J_{S+R}$; this solution explains the distribution of additional profits and risk preference coefficients for fresh produce suppliers and retailers $(\varsigma_s, \varsigma_r)$ is proportional to, that is, the greater the risk appetite coefficient, the more extra profit it distributes; however, the profit distribution parameter is: $k = \frac{\varsigma_s k_1}{\varsigma_s+\varsigma_r} + \frac{\varsigma_r k_2}{\varsigma_s+\varsigma_r}$, so the wholesale price of agricultural products is:

$$w^T = c_{s0} + c_1 g^T + \frac{k}{a - bp^T + \theta g^T} = c_{s0} + c_1 g^T + \frac{1}{a - bp^T + \theta g^T}\left(\frac{\varsigma_s k_1}{\varsigma_s+\varsigma_r} + \frac{\varsigma_r k_2}{\varsigma_s+\varsigma_r}\right).$$

When fresh produce supply chain operators have the same preference for additional profits, that is, the channel members share the additional profit equally, that is, share profit equally. Otherwise, when $\varsigma_s > \varsigma_r$ hour, suppliers can set a high wholesale price of fresh produce to get more profit and vice versa.

## 6. Numerical analysis

The theoretical results proposed in this paper are numerically simulated using Matlab software to verify their effectiveness. Mainly studied the effectiveness of preservation $\zeta$ and operational inefficiency factor $c_1$ effects on equilibrium outcomes and pricing strategies, also explores the impact on the coordination of fresh produce supply chains. The benchmark parameter assignments in the model are mainly drawn from the research of Yang and Tang (2019), Liu et al. (2021c), and Yan and Han (2022). The specific values are shown in Table 2.

### 6.1. Freshness effectiveness $\zeta$ impact on equilibrium outcome

This section studies the effectiveness of preservation $\zeta$ impact on equilibrium outcomes, i.e., in the life cycle of fresh produce $[0, T]$ inside $T = 5$, preservation effectiveness in centralized and decentralized scenarios $\zeta$ impacts the steady-state equilibrium of the fresh agricultural product supply chain. First, maintain the effective coefficient of fresh-keeping input $\lambda$, input cost coefficient of preservation $\eta$, and price elasticity coefficient. Operational inefficiency factor $c_1$. The values of other parameters, remain unchanged, and secondly, adjust the freshness contribution rate

**Table 2.** Parameter values.

| Parameter | $a$ | $b$ | $\theta$ | $\lambda$ | $\rho$ | $\delta$ | $c_{s0}$ | $c_{r0}$ | $c_1$ | $\eta$ | $g_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Value | 20 | 2 | 1 | 1 | 0.1 | 0.4 | 0.6 | 0.4 | 0.4 | 2 | 0.98 |

Note: Under this parameter, $\zeta = 0.1$.

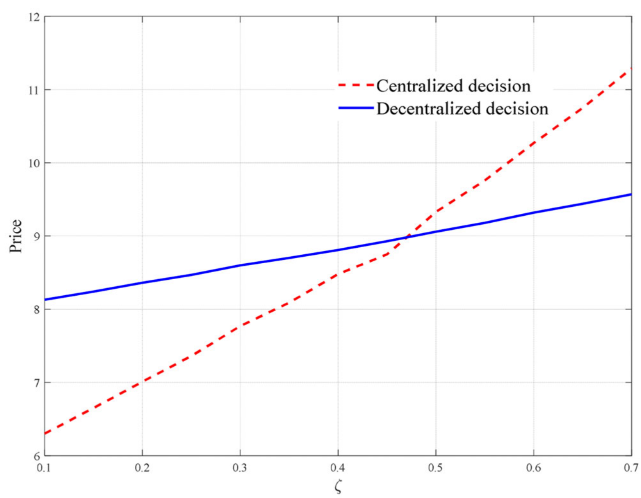


**Figure 1.** $\zeta$ influence on the selling price of fresh agricultural products.
Source: Data from Yang & Tang (2019), Liu et al. (2021a, 2021b, 2021c).

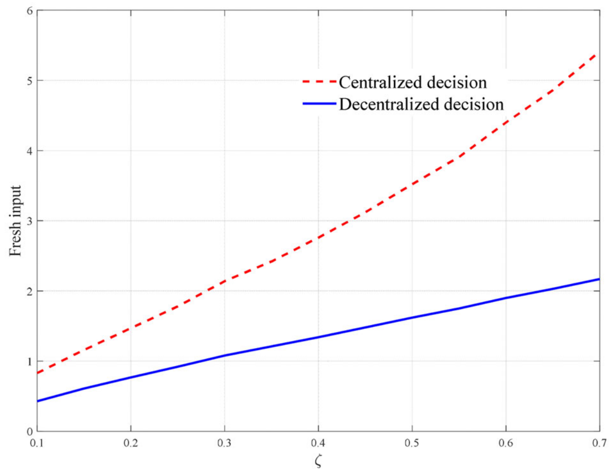


**Figure 2.** ζ influence on the input of fresh agricultural products.
Source: Data from Yang & Tang (2019), Liu et al. (2021a, 2021b, 2021c).

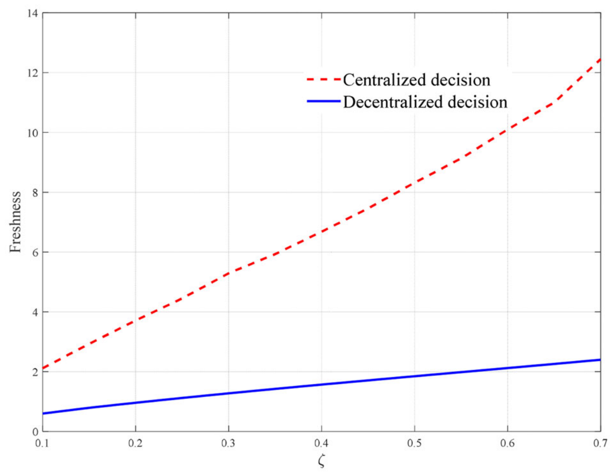


**Figure 3.** ζ influence on the freshness of fresh agricultural products.
Source: Data from Yang & Tang (2019), Liu et al. (2021a, 2021b, 2021c).

coefficient $\theta$ make it increase from 0.1 to 0.7 at a rate of 0.1, i.e., $\theta = 1, 1.15, 1.28, 1.38, 1.48, 1.57, 1.65$. Finally, the effectiveness of fresh-keeping was plotted $\zeta$ a graph of the impact on equilibrium price, freshness input, freshness, and channel profit. As shown in Figures 1–4. (The data in Figures 1–13 are obtained by assigning the parameters to the relevant models).

It can be clearly seen from Figures 1–4 that when the coefficient of effectiveness of preservation $\zeta$ increases, the equilibrium in both the centralized and decentralized scenarios increases, this shows that whether it is a centralized or decentralized channel when fresh agricultural product supply chain operators face high fresh-keeping effectiveness, will increase investment in preservation, thereby improving the freshness of agricultural products, setting higher sales prices (consumers are willing to pay higher fees for agricultural products with high freshness), and obtaining more profits.

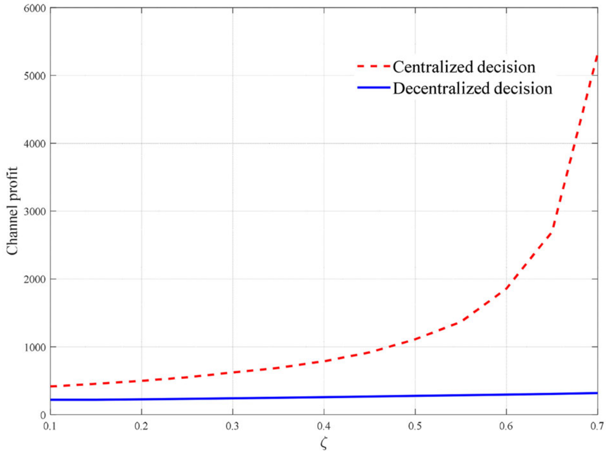


**Figure 4.** ζ influence on the channel profit of fresh agricultural products.
Source: Data from Yang & Tang (2019), Liu et al. (2021a, 2021b, 2021c).

As shown in Figure 1, when the preservation effectiveness is below the threshold $\bar{\zeta}$ hour, the sales price of fresh agricultural products in the complete scenario is lower than that in the decentralized scenario. When the fresh-keeping effectiveness coefficient is higher than this threshold, the sales price in the centralized scenario is higher than in the decentralized scenario. This conclusion thoroughly verifies inference 3. However, this shows that the concentration scenario sometimes leads to low sales prices. Under the centralized channel, substantial fresh-keeping inputs will produce high freshness of agricultural products so that operating companies can set higher sales prices. As shown in Figure 1, for example, when shandong shouguang agricultural products comprehensive wholesale market co., ltd. (supplier) has an effective coefficient of freshness effort level input of 1, the selling price of the company's fresh agricultural products in the centralized scenario of yonghui supermarket (retailer) is 6.30, while the selling price in the decentralized scenario is 8.13; when shandong shouguang agricultural products comprehensive wholesale market co. The above examples are sufficient to show that different values of the parameters affect the optimal solution of the selling price of the operating companies.

Compared with the decentralized scenario, the freshness preservation input, freshness, and profit are higher in the centralized scenario (as shown in Figures 2–4), which thoroughly verifies inference 4. Furthermore, with the increase in the effectiveness of fresh-keeping, the gap in fresh-keeping input, freshness, and channel profit under the two scenarios becomes larger and larger, indicating that when the effectiveness of fresh-keeping is greater, the balance of the fresh agricultural product supply chain increases in the centralized scenario faster.

### 6.2. Operational inefficiencies $c_1$ influence on the pricing strategy of fresh agricultural products

According to inference 2 and the benchmark parameter values in Table 2, $0 < c_1 < \frac{\theta}{b}$ can be drawn, $c_1$ value $0 < c_1 < 0.5$. $g_T^C$ value $0 < g_T^C < 24.87$ due to $g_T^C < 24.87$,

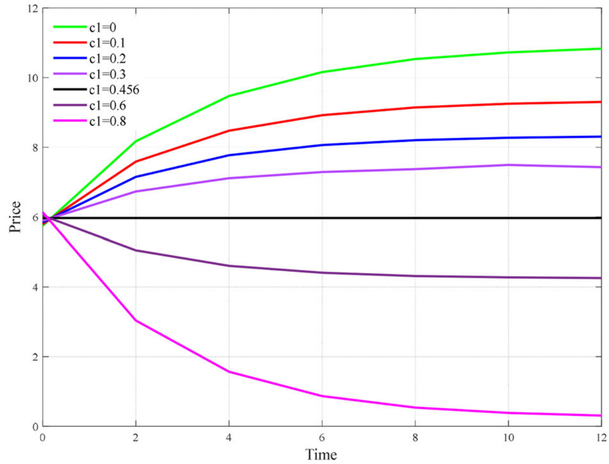


**Figure 5.** Influence on the pricing strategy of fresh agricultural products $c_1$.

however after $g_0 - \frac{4b\eta\lambda^2(a-bc_0)(\theta-b\tilde{c}_1)}{(b\rho\eta+\Delta_3)(\Delta_3-b\eta(\rho-2\delta))} = 0$ threshold can be solved $\tilde{c}_1 = 0.456$. Figure 5 $c_1$ pick shows 0, 0.1, 0.2, 0.3, 0.456, 0.6, 0.8 equilibrium price in time interval under different value scenarios $[0, 12]$ (in the life cycle of fresh produce $[0, T]$ within) changes.

It can be seen from Figure 5 that when $c_1 = 0.456$ hour, optimal fresh produce sales price over the entire time range $[0, 12]$ remain unchanged. Therefore, $\tilde{c}_1$ is regarded as the switching point of the operating enterprise's pricing strategy. When the sale price of agricultural products decreases over time until the price stabilizes ($c_1 = 0.6, c_1 = 0.8$), the operating company chooses to use a skimming pricing strategy. When agricultural product sales increase over time until the price stabilizes ($c_1 = 0, c_1 = 0.1, c_1 = 0.2, c_1 = 0.3$), operating companies will choose to use penetration pricing strategies. However, when $c_1 = 0$ hour, i.e., no operational inefficiencies (high freshness does not come with marginal cost) hour, stable sales prices are high. When $c_1 = 0$ increases to $c_1 = 0.1$, the price gap between the two changes considerably, but when $c_1 = 0.1$ increase to $c_1 = 0.2$ in $c_1 = 0.3$ hour, the change in the price gap between the three is small, which fully shows that the existence of operational inefficiency has dramatically reduced the sales price of agricultural products. From the perspective of fresh agricultural product operating companies, low operational inefficiency (what the company pursues) enables the operating company to obtain more marginal profits through penetration pricing. At the same time, the operating company can increase investment in fresh-keeping to improve the freshness of agricultural products. To attract more demand from consumers. However, when the operational inefficiency is high, the operating company loses the enthusiasm to invest in fresh-keeping efforts, resulting in the lower freshness of agricultural products (low freshness so that consumers have low purchasing intentions), but in order to ensure higher profit margins, the operating company chooses to use a skimming pricing strategy.

Research suggests switching points for operating firms' pricing strategy $\tilde{c}_1$ mainly affected by the initial freshness value of agricultural products $g_0$ effect, as shown in

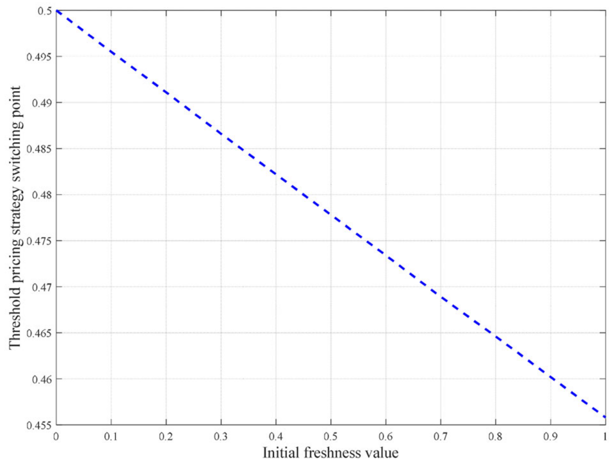


**Figure 6.** Initial freshness value Switch point for pricing strategy $\tilde{c}_1$ impact.

Figure 6. It can be seen from Figure 6 that the pricing strategy switching point $\tilde{c}_1$ with initial freshness value $g_0$ is less. However, when $g_0 = 1$ hour, down to the switch point (the switch point $\tilde{c}_1$ and $g_0 = 0.98$ value) below, it shows that when the initial freshness value is high, a lower operational inefficiency ($c_1 = 0.456$) enables fresh produce operators to switch from penetration pricing to skimming pricing.

### 6.3. Other parameters influence on the pricing strategy of fresh agricultural products

Figures 7 and 8 show that the selling prices under the centralized and decentralized scenarios keep decreasing as ρ and δ increase. As shown in Figure 9, the selling price of fresh produce under the centralized scenario is lower than that under the decentralized scenario when λ is below the threshold $\bar{\lambda} = 2.15$. When λ is above this threshold, the selling price under the centralized scenario is higher than that under the decentralized scenario; however, this illustrates that the centralized scenario does not necessarily lead to a low selling price.

### 6.4. Freshness effectiveness ζ the impact on the coordination of fresh agricultural product supply chain

As shown in Figure 10, Figure 10 depicts the effectiveness of preservation ζ on coordination parameters $k$ impact. Curve $k_1$ and $k_2$ Figure 10 is divided into upper, middle, and lower regions (region 1-sw-rl, region 2-sw-rw, region 3-sl-rw), when $k$ in zone 1 and zone 2, $J_S^T(k) > J_S^D$, $k$ when in zone 2 and zone 3, $J_R^T(k) > J_R^D$. Currently, region 1-sw-rl is the supplier win-retailer loss area, region 2-sw-rw is the win-win area, and region 3-sl-rw is the supplier loss-retailer win area.

Figure 10 shows that when $k$ in zone 2, the two pricing systems can successfully coordinate the supply chain and benefit every fresh produce operating company. When the effective coefficient of freshness keeps increasing ζ, regions 2 and 3 keep

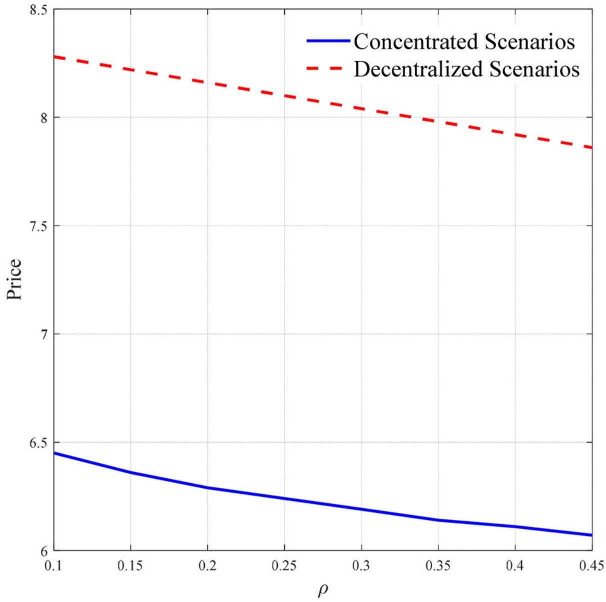


**Figure 7.** Effect of ρ on sales price.

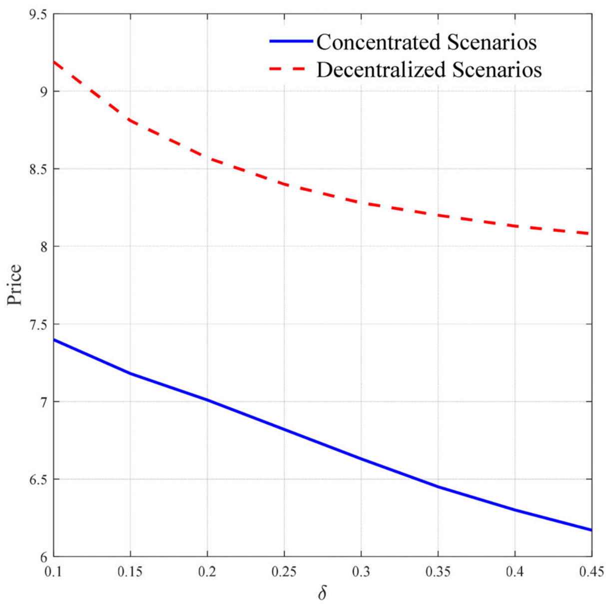


**Figure 8.** Effect of δ on sales price.

growing, while region 1 keeps shrinking. This means a significant coefficient of freshness effectiveness, making it easier for suppliers and retailers to negotiate a win-win situation $\zeta$, improved agility for fresh produce suppliers to coordinate supply chains.

As shown in Figures 11 and 12, with the increase in preservation effectiveness, the profits of suppliers and retailers under the decentralized scenario and the two-part

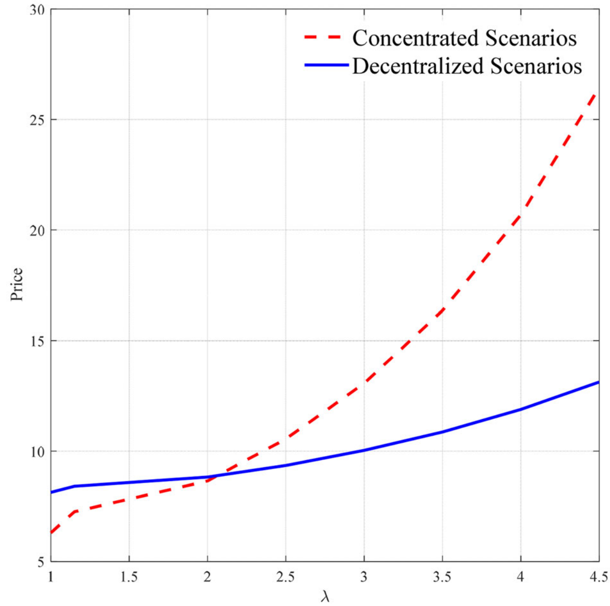


Figure 9. Effect of λ on sales price.

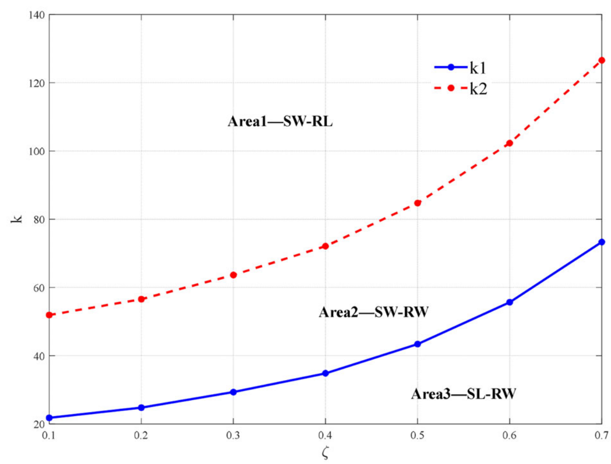


Figure 10. The impact on the coordination of fresh agricultural product supply chain ζ.

pricing contract continue to rise, indicating that when the preservation effectiveness is greater, the supply under the two-part pricing contract increases. The upward trend in the profits of merchants and retailers is more evident than that in the decentralized scenario. Therefore, the two pricing contracts can effectively coordinate the supply chain of fresh agricultural products. As shown in Figures 4 and 5, when the freshness effectiveness coefficient of shandong shouguang agricultural products wholesale market co., ltd (supplier) is 0.1, the company's profit (supplier) under the two-part pricing contract is 229.67. The profit under the decentralized scenario is 205.03, with a

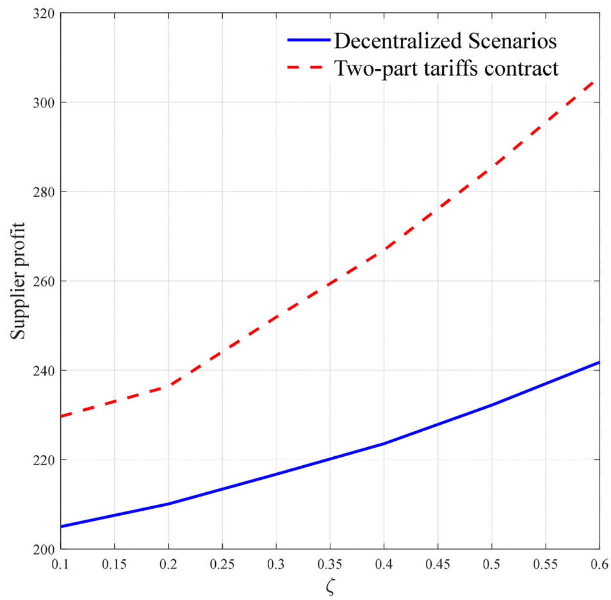


**Figure 11.** The effect of fresh-keeping effectiveness on supplier profits.

difference of 24.64, i.e., the profit obtained by the company (supplier) under the two-part pricing contract is 24.64 more than that under the decentralized 24.64 more profit under the two pricing contracts than under the decentralized scenario, while the profit of yonghui supermarket (retailer) is 119.67 under the two pricing contracts and 94.84 under the decentralized scenario, with a difference of 24.83 profit, i.e., the profit of yonghui supermarket (retailer) is 24.83 more profit under the two pricing contracts than under the decentralized scenario; when shandong shouguang agricultural products comprehensive wholesale market co. (supplier) has a freshness effectiveness factor of 0.5, the company's (supplier) profit under the two-part pricing contract is 285.38, and the profit under the decentralized scenario is 232.21, i.e., the company's (supplier) profit under the two-part pricing contract is 53.17 more than the profit under the decentralized scenario. In contrast, the profit of yonghui supermarket (retailer) under the two-part pricing contract is. The above example illustrates that the two-part pricing contract enables the supplier and retailer to improve pareto.

### 6.5. The impact of operational inefficiencies on fresh produce supply chain coordination $c_1$

As shown in Figure 13, Figure 13 depicts the $c_1$ coefficient of coordination $k$ impact. As in Figure 10, this map is divided into three regions: upper, middle, and lower: region 1-sw-rl, region 2-sw-rw, and region 3-sl-rw.

It is clear from Figure 13 that when operational inefficiencies $c_1$ when increasing continuously, area 1 keeps increasing, while area 1 and area 2 keep shrinking. The results of this study show that when fresh agricultural products operating enterprises

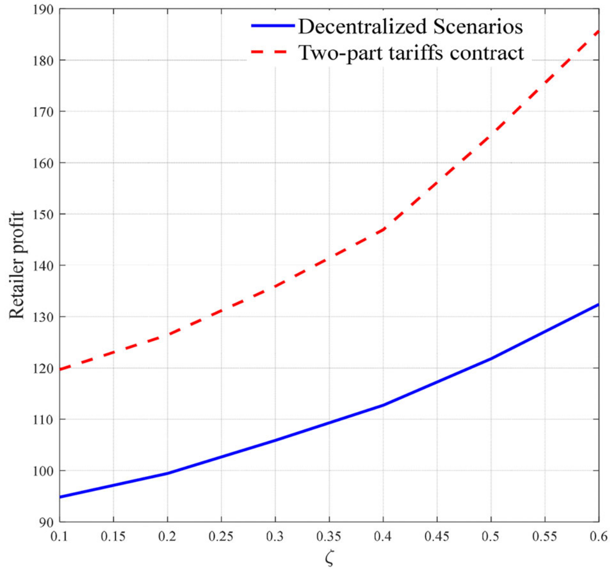


Figure 12. The effect of preservation effectiveness on retailers' profits.

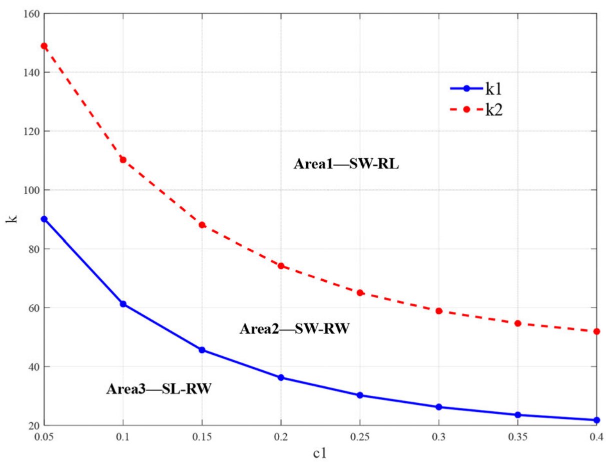


Figure 13. Impact on the coordination of fresh agricultural product supply chain $c_1$.

are operating inefficiently $c_1$ when higher, it is difficult to coordinate the supply chain satisfactorily.

## 7. Conclusion

Fresh agricultural products have their characteristics of decreasing freshness with time. Based on this, this paper mainly studies the dynamic pricing and fresh-keeping input decisions of operating companies considering operational inefficiency under the freshness of fresh agricultural products and designs a supplier with two wholesale prices, that is, two pricing contracts to coordinate the supply chain. The research results show that the sales price of fresh agricultural products in the complete scenario is not necessarily lower than that in the decentralized scenario; when the initial freshness is high, there is an operational inefficiency threshold ($c_1 = 0.456$), which can make the pricing strategy of fresh agricultural product operators switch from penetration pricing to skimming pricing; when the supplier designs the two pricing as a function of the freshness of the produce, it can coordinate the supply chain satisfactorily; the ability of fresh produce suppliers to coordinate supply chains increases with preservation effectiveness $\zeta$ increasing and increasing, with operational inefficiencies $c_1$ of increasing and decreasing. The management implications of this paper are as follows: first, to provide reference or guidance for fresh agricultural product operators to formulate sales price strategies when low operational inefficiency (fresh agricultural products suppliers bring high marginal costs for freshness preservation, for example, when a fresh-keeping (cold chain) transport vehicle has a high unloaded rate during the return journey), the operating enterprise can obtain more profits by increasing the sales price, when there is high operational inefficiency (low marginal costs for suppliers to keep fresh), the operating firm can profit by lowering the selling price. Second, provide theoretical support or a basis for fresh agricultural product suppliers to formulate reasonable wholesale price contracts. Designing two pricing functions as a function of freshness, suppliers of fresh agricultural products can make the total profit of the supply chain in the decentralized scenario reach the maximum profit in the centralized scenario. The profits in the two scenarios are equal and can also improve the retailer's profit. Third, a coordinated contract between fresh produce suppliers and retailers can be negotiated to improve their profit margins to achieve a 'win-win' situation.

In this paper, only fresh produce suppliers are considered for fresh produce preservation. However, future work may consider introducing retailers for fresh produce preservation or joint preservation between suppliers and retailers. In addition, the paper does not consider other costs of suppliers and retailers, such as the management costs of suppliers and the sales, inventory, and management costs of retailers, etc. However, the costs of suppliers and retailers can be considered in future work. Finally, the government will subsidize the operating companies with funds to encourage suppliers to increase freshness input. The article does not consider government subsidies; however, future work can be considered to introduce the study of dynamic pricing and freshness input strategy under government funds (price) subsidy is also of practical significance.

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