Decision Making on Preservation Efforts of Agricultural Products Considering Sales Period under Different Supply Chain Structures

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Abstract. This study focuses on the fresh agricultural product supply chain composed of suppliers and sellers, considering both parties' efforts in preserving freshness and the sales period of agricultural products, as well as the impact of freshness decline on market demand. A decision model for different supply chain structures under Stackelberg game theory is constructed, and the differences in preservation effort level and supply chain profit between centralized and decentralized decision-making modes are systematically analyzed. Research has shown that centralized decision-making significantly improves the overall profit and product freshness of the supply chain by synergistically optimizing the preservation investment and pricing of suppliers and sellers, while decentralized decision-making leads to insufficient preservation efforts and efficiency losses due to dual marginal effects. The research results provide a theoretical basis for the design of preservation strategies in the supply chain of fresh agricultural products, and provide practical insights for reducing losses and improving the sustainability of the supply chain.

Keywords: fresh food supply chain; Efforts to preserve freshness; Sales period

1 Introduction

In recent years, the huge losses generated by fresh agricultural products in the supply chain circulation have become a hot issue of concern. Due to the perishable and difficult preservation of fresh agricultural products[1], as well as the lack of timely pre cooling in the production area,, and improper preservation in the sales process, a large amount of losses are caused. According to statistics, the postpartum loss rate of fruits, vegetables, and potatoes in China is as high as 15% -25%, with an annual loss of nearly 200 million tons[2]. Every link in the circulation of fresh agricultural products may affect the final freshness and quality of the products.

There is currently limited literature on the joint responsibility of both parties in the supply chain for preservation work. There are even fewer literature on preservation for both parties considering the sales period. Regarding the preservation of fresh agricul-

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tural products, existing research has mostly focused on independent preservation by one party [3,4] and joint preservation by multiple parties [5,6]. In terms of preservation strategy, Huang and Qiufang[3]explored the optimal preservation strategy for electronic retailers when using third-party logistics for separate preservation. Therefore, in order to effectively reduce the loss of fresh agricultural products, it is necessary to ensure the freshness of the entire supply chain of fresh agricultural products. All nodes in the supply chain, including suppliers and sellers, need to work together. Not only should suppliers carry out preservation work in the initial stage, but sellers also need to implement preservation work in subsequent stages.

In view of this, in response to the shortcomings of existing research, this article considers the joint responsibility of member suppliers and sellers in the supply chain for freshness preservation. The secondary supply chain composed of suppliers and sellers is taken as the research object, and the cooperation of fresh agricultural product supply chain members for freshness preservation is considered. Centralized and decentralized models are constructed, and the two models are compared and analyzed.

2 Problem Description and Research Hypothesis

2.1 Problem Description

A fresh agricultural product supply chain consisting of a fresh food supplier (r) and a fresh food seller (s). Among them, it is considered that within a limited sales cycle T, the supplier is responsible for the initial stage (picking, packaging, and transportation) of preservation, while the retailer is responsible for the subsequent preservation work after receiving fresh products.

2.2 Research Hypothesis

Assumption 1: Referring to Cao Xiyu [6], the freshness of fresh agricultural products θ is a decreasing function of time t:$\theta(t) = \theta_0 + e_s + e_r - \varphi(\frac{t}{T})^2$, $t \in [0, T]$.Where $\theta_0 \in (0,1)$ represents the initial freshness of the fresh agricultural product; φ represents the maximum freshness decay after T; T represents time;e_s（$0 < e_s < 1$）and（$0 < e_r < 1$） respectively represent the level of preservation efforts made by suppliers and sellers.

Assumption 2: The market demand d for fresh agricultural products is related to the price p and freshness θ. Referring to the research of Wu Yunting et al.[7], the demand function is $d(t) = d_0 - \alpha p + \beta\theta(t)$. Among them, d_0 is the market size of fresh agricultural products, α and β are the sensitivity coefficients of consumers to price and freshness, θ is the freshness of fresh agricultural products, and $\alpha > 0, \beta > 0$.

Assumption 3: Referring to the research of Wu Yunting et al. [7], assume that the supplier's preservation cost $C_s = \frac{1}{2}k_s e_s^2$, and the seller's preservation cost $C_r = \frac{1}{2}k_r e_r^2$. Among them, k_s and k_r represent the cost impact coefficients of the preservation efforts of suppliers and sellers. The value of k is set to be sufficiently large. The superscript "*" in the article represents the optimal solution.

3 Model Establishment and Solution

3.1 Centralized Decision Model (C Model)

Under the centralized decision-making model, suppliers and sellers work together as a whole to make decisions. According to the previous assumption, the market demand function for fresh agricultural products at time t is $\mathrm{d(t)} = d_0 - \alpha p + \beta(\theta_0 + e_s + e_r - \varphi\left(\frac{t}{T}\right)^2)$. Therefore, $\mathrm{d} = \int_0^T [\mathrm{d(t)}]\,dt = \left(d_0 - \alpha p + \beta\left(\theta_0 + e_s + e_r - \frac{\varphi}{3}\right)\right)T$. Profit of supply chain system:

$$\pi_C = (p-c)\left(d_0 - \alpha p + \beta\left(\theta_0 + e_s + e_r - \frac{\varphi}{3}\right)\right)T - \frac{1}{2}k_s e_s^2 - \frac{1}{2}k_r e_r^2$$

First, calculate the first derivative of e_s,$e_r$and p to establish the hessian matrix: $H^C(e_s, e_r, p) = \begin{bmatrix} -k_s & 0 & \beta \mathrm{T} \\ 0 & -k_r & \beta \mathrm{T} \\ \beta \mathrm{T} & \beta \mathrm{T} & -2\alpha T \end{bmatrix}$, Because $k_i > 0$ is sufficiently large, and $\alpha > 0$, $\beta > 0$, the first-order principal equation $\mathrm{H}_1^C(e_s, e_r, p) = -k_s < 0$, the second-order principal equation $\mathrm{H}_2^C(e_s, e_r, p) = k_s k_r > 0$, and the third-order principal equation $\mathrm{H}_3^C(e_s, e_r, p) = -2\alpha \mathrm{T} k_s k_r + T^2\beta^2(k_s + k_r) < 0$, so the hessian matrix is negatively definite and the optimal solution exists and is unique. By combining $\frac{\partial \pi^C}{\partial e_s} = 0$, $\frac{\partial \pi^C}{\partial e_r} = 0$, $\frac{\partial \pi^C}{\partial p} = 0$, Can be obtained:

$$e_s^* = \frac{T\beta k_r(-3d_0 + 3\alpha c + \beta(-3\theta_0 + \varphi))}{3(\mathrm{T}\beta^2(k_s + k_r) - 2\alpha k_s k_r)}, \quad e_r^* = \frac{T\beta k_s(-3d_0 + 3\alpha c + \beta(-3\theta_0 + \varphi))}{3(\mathrm{T}\beta^2(k_s + k_r) - 2\alpha k_s k_r)}$$

$$p^* = \frac{3c\mathrm{T}\beta^2 k_s + k_r(3c\mathrm{T}\beta^2 + (-3(d_0 + \alpha c + \beta\theta_0) + \beta\varphi)k_s)}{3(\mathrm{T}\beta^2(k_s + k_r) - 2\alpha k_s k_r)}, \quad \pi_c^* = \frac{T k_s k_r(-3d_0 + 3\alpha c + \beta(-3\theta_0 + \varphi))^2}{18(\mathrm{T}\beta^2(k_s + k_r) - 2\alpha k_s k_r)}$$

3.2 Decentralized Decision Model (D Model)

Under the D model,suppliers and sellers aim to maximize their respective interests. The decision-making process is as follows: Firstly, the supplier decides on the wholesale price w and preservation effort es of fresh agricultural products, and then the seller determines their preservation effort er and sales price p based on the supplier's decision. The total profit of suppliers, sellers, and supply chain systems is:

$$\pi_s = (w-c)d - C_s = (w-c)\left(d_0 - \alpha p + \beta\left(\theta_0 + e_s + e_r - \frac{\varphi}{3}\right)\right)T - \frac{1}{2}k_s e_s^2 \quad (1)$$

$$\pi_r = (p-w)d - C_r = (p-w)\left(d_0 - \alpha p + \beta\left(\theta_0 + e_s + e_r - \frac{\varphi}{3}\right)\right)T - \frac{1}{2}k_r e_r^2 \quad (2)$$

$$\pi_D = (p-c)\left(d_0 - \alpha p + \beta\left(\theta_0 + e_s + e_r - \frac{\varphi}{3}\right)\right)T - \frac{1}{2}k_s e_s^2 - \frac{1}{2}k_r e_r^2 \quad (3)$$

Using the reverse solving method: First, find the first-order derivative of the salesperson's profit function (2) regarding e_r and p.So obtain the hessian matrix $H^D(e_r,p) = \begin{bmatrix} -k_r & \beta T \\ \beta T & -2\alpha T \end{bmatrix}$, the hessian matrix is negatively determined and there exists an optimal solution. the response function of the seller's preservation effort level and sales price can be obtained:

$$e_r(e_s,w) = \frac{T\beta(-3d_0-3\beta\theta_0+3\alpha w-3\beta e_s+\beta\varphi)}{3(\mathrm{T}\beta^2-2\alpha k_r)} \tag{4}$$

$$\mathrm{p}(e_s,w) = \frac{3\mathrm{Tw}\beta^2-k_r(3d_0+3\beta\theta_0+3\alpha w+3\beta e_s-\beta\varphi)}{3(\mathrm{T}\beta^2-2\alpha k_r)} \tag{5}$$

Then the supplier decides on $\mathrm{e_s}$ and w. Substituting (4) and (5) into (1) yields:

$$\pi_s^D = \frac{-3T\beta^2 k_s e_s^2+2\alpha k_r(\mathrm{T}(c-w)(3d_0+3\beta\theta_0-\beta\varphi-3\alpha w)+3T\beta e_s(c-w)+3k_s e_s^2)}{6(\mathrm{T}\beta^2-2\alpha k_r)} \tag{6}$$

Find the first-order derivative of $\mathrm{e_s}$and w in the supplier profit function (5), establish the hessian matrix $\mathrm{H}(e_s,w) = \begin{bmatrix} \frac{-T\beta^2 k_s+2\alpha k_s k_r}{\mathrm{T}\beta^2-2\alpha k_r} & \frac{-T\alpha\beta k_r}{\mathrm{T}\beta^2-2\alpha k_r} \\ \frac{-T\alpha\beta k_r}{\mathrm{T}\beta^2-2\alpha k_r} & \frac{2\mathrm{T}\alpha^2 k_r}{\mathrm{T}\beta^2-2\alpha k_r} \end{bmatrix}$, so the hessian matrix is negatively determined and there exists an optimal solution. we can obtain:

$$e_s^* = \frac{T\beta k_r(-3d_0-3\beta\theta_0+3\alpha c+\beta\varphi)}{3(\mathrm{T}\beta^2(2k_s+k_r)-4\alpha k_s k_r)} \tag{7}$$

$$w^* = \frac{-T\beta^2 k_s(-3d_0-3\beta\theta_0-3\alpha c+\beta\varphi)-\alpha k_r(k_s(6d_0+6\beta\theta_0+6\alpha c-2\beta\varphi)-3T\beta^2 c)}{3\alpha(\mathrm{T}\beta^2(2k_s+k_r)-4\alpha k_s k_r)} \tag{8}$$

the optimal solutions for the seller's effort level in preserving freshness, e_r, and the sales price, p, can be obtained:

$${e_r}^{D*} = \frac{T\beta k_s(-3d_0-3\beta\theta_0+3\alpha c+\beta\varphi)}{3(\mathrm{T}\beta^2(2k_s+k_r)-4\alpha k_s k_r)} \tag{9}$$

$$p^{D*} = \frac{-T\beta^2 k_s(-3d_0-3\beta\theta_0-3\alpha c+\beta\varphi)-3\alpha k_r(k_s(3d_0+3\beta\theta_0+\alpha c-\beta\varphi)-T\beta^2 c)}{3\alpha(\mathrm{T}\beta^2(2k_s+k_r)-4\alpha k_s k_r)} \tag{10}$$

3.3 Comparison and Analysis

Below, we compare and analyze the optimal results under centralized and decentralized decision-making, and obtain the following proposition:

Proposition 1: The level of preservation efforts of suppliers and sellers under centralized decision-making is greater than that under decentralized decision-making:$e_s^{C*} > e_s^{D*}$, $e_r^{C*} > e_r^{D*}$.

Proof: $e_s^{C*} - e_s^{D*} = \frac{T\beta k_s k_r(\beta\varphi+3\alpha c-3d_0-3\beta\theta_0)(2\alpha k_r-T\beta^2)}{3(2\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-4\alpha k_s))(\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-2\alpha k_s))} > 0$, $e_r^{C*} - e_r^{D*} = \frac{T\beta {k_s}^2(\beta\varphi+3\alpha c-3d_0-3\beta\theta_0)(2\alpha k_r-T\beta^2)}{3(2\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-4\alpha k_s))(\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-2\alpha k_s))} > 0$

Centralized decision-making eliminates double marginal effects, collaboratively optimizes decision variables, and dynamically coordinates time sensitivity, prompting supply chain members to increase their efforts in freshness preservation and achieve maximum overall benefits. However, decentralized decision-making results in preservation investment being lower than the socially optimal level due to local conflicts of interest and insufficient coordination.

Proposition 2: The profit of the supply chain system under centralized decision-making is greater than that decentralized decision-making: $\pi^{C*} > \pi^{D*}$.

Proof: the supplier's profit $\pi_s^{D*} = \frac{-\mathrm{T}k_s k_r(-3d_0-3\beta\theta_0+\beta\varphi+3\alpha c)^2}{18(2\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-4\alpha k_s))}$,the seller profit $\pi_r^{D*} = \frac{-Tk_s{}^2 k_r(T\beta^2-2\alpha k_r)(-3d_0-3\beta\theta_0+\beta\varphi+3\alpha c)^2}{18(2\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-4\alpha k_s))^2}$,the profit of the supply chain system is $\pi^{D*} = \frac{-Tk_s{}^2 k_r(T\beta^2-2\alpha k_r)(-3d_0-3\beta\theta_0+\beta\varphi+3\alpha c)^2}{18(2\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-4\alpha k_s))^2}$, $\pi^{C*} - \pi^{D*} = \frac{Tk_r k_s{}^3(3d_0-3\alpha c+3\beta\theta_0-\beta\varphi)^2(2\alpha k_r-T\beta^2)^2}{18\left(2\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-4\alpha k_s)\right)^2(\mathrm{T}\beta^2 k_s+k_r(\mathrm{T}\beta^2-2\alpha k_s))} > 0$, because $k_s k_r$ is sufficiently large, $\pi^{C*} > \pi^{D*}$.

Centralized decision-making maximizes the overall profit of the supply chain by eliminating double marginal effects, coordinating preservation efforts, and dynamically coordinating time sensitivity. Due to local conflicts of interest, free riding effects, and insufficient coordination, decentralized decision-making results in insufficient investment in preservation, high prices, and limited market demand, ultimately leading to profit losses.

4 Conclusions

This study is based on Stackelberg game theory, considering both parties' efforts in preservation and the sales period of agricultural products. A decision model for collaborative preservation between suppliers and sellers in the fresh agricultural product supply chain is constructed. By comparing the equilibrium results under centralized and decentralized decision-making modes, the impact of dual subject preservation effort decisions on the supply chain is revealed. The main conclusions are as follows:

(1) Centralized decision-making significantly improves the overall preservation investment of the supply chain by jointly optimizing the supplier's preservation effort level $\mathrm{e}_\mathrm{s}^{\mathrm{C}*}$ and the seller's preservation effort level $\mathrm{e}_\mathrm{r}^{\mathrm{C}*}$ and the pricing strategy $\mathrm{p}^{\mathrm{C}*} < \mathrm{p}^{\mathrm{D}*}$. Make the total profit of the supply chain $\pi^{\mathrm{C}*}$ higher than decentralized decision-making. So centralized decision-making can better coordinate the interests of both parties and achieve higher overall benefits.However, decentralized decision-making leads to losses in supply chain profits due to local conflicts of interest, free riding effects, and insufficient coordination.

(2) The sales period, as a key factor affecting the freshness decline of fresh agricultural products, has a significant regulatory effect on supply chain preservation decisions. Centralized decision-making can effectively slow down the rate of freshness decline, reduce losses caused by time accumulation, and enhance market demand response capabilities by coordinating and planning the preservation investment and

pricing strategy throughout the entire sales cycle T. The longer the sales period, the more effort the seller puts into preserving the freshness, the higher the freshness, and the higher the purchasing power of consumers. In contrast, under decentralized decision-making, it is difficult for both parties to dynamically match the time sensitivity of preservation efforts and sales periods due to local interest orientation, resulting in an accelerated decline in freshness in the later stage and weakening the overall competitiveness of the supply chain.

(3) Although centralized decision-making can maximize supply chain benefits, it faces challenges in practice such as information barriers, conflicts of interest, high coordination costs, and insufficient adaptability to dynamic environments. Suppliers and sellers can balance member rights and gradually achieve the transformation of theoretical advantages into practical effectiveness through phased pilot programs, contractual incentive mechanisms, and digital tools.

(4) Provide real-time monitoring, demand forecasting, and dynamic contract design solutions for preservation work through technologies such as the Internet of Things and data analysis. By tracking environmental data through sensors, optimizing inventory through machine learning, and ensuring contract transparency through blockchain, new momentum is injected into improving supply chain preservation efficiency and synergy.

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