AN OPTIMAL FRESHNESS-KEEPING EFFORT MODEL FOR FRESH PRODUCE WITH CONSTRAINTS OF SPECIAL FUNDS

BING ZHOU
Research Center for Economy of Upper Reaches of the Yangtse River
Chongqing Technology and Business University, Chongqing 400067, China
School of Accounting, Chongqing Technology and Business University
Chongqing 400067, China

YUFENG LI∗
Research Center for Economy of Upper Reaches of the Yangtse River
Chongqing Technology and Business University, Chongqing 400067, China

XIN FANG
School of Management Science and Engineering, Chongqing Technology
and Business University, Chongqing 400067, China

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Abstract. The quality deterioration in the post-production process of fresh products is very serious, and the life-cycle freshness-keeping technology investment is an effective way to reduce the deterioration. Because the investment cost is high in practice, enterprises need to allocate special funds for each stage to maximize their marginal revenue. In this paper, we use freshness to characterize the quality level of fresh products and investigate a maximize marginal revenue problem where a firm assigns special funds for the freshness-keeping effort with each post-production process. An optimal freshness-keeping model with the constraints of special funds is discussed. The investigation shows that both the optimal freshness-keeping effort and the closed-form optimal solutions of enterprises exist uniquely. A reasonable freshness-keeping investment in different post-production processes can improve the performance of enterprises with limited fund constraints. We then simulate the effect rules of funds constraint on these solutions based on numerical analysis and give some management insights.

1. Introduction. Coordinating the freshness of fresh produce and freshness-keeping input level is conducive to adjusting the relationship between market supply and demand, which helps to improve enterprise performances. However, the freshness-keeping costs is high and the fresh enterprises generally lack funds. The data shows that 85.1% of the surveyed enterprises have experienced financial pressure, and the pain points of funds resources account for the highest proportion[39].
Funds shortage is an objective problem that must be addressed squarely in enterprise operations. At the same time, the post-production quality loss of fresh produce is very serious, due to the perishable characteristics and short life cycle. According to the China Economic Information Daily, China’s agricultural produce lose more than 43 billion dollars annually, which is equivalent to the annual output value of 100 million hectares of arable land. Reducing the loss of fresh produce can be achieved by investing in a costly full cold chain or improving packaging/handling technology. For example, Jingdong invested 10 billion CNY, Future Life and Beijing Capital Agribusiness Group invested 3 billion CNY to build a cold chain logistics system. The high investment in freshness-keeping technology has aggravated the funds shortage of fresh enterprises, and has also increased the difficulty of decision-making for fresh enterprises with limited funds. Therefore, studying the decision-making of freshness-keeping input under the funds constraints is of great significance for enterprises to realize reasonable freshness-keeping input level and obtain more profits.

Investing in freshness-keeping strategies can reduce the loss of fresh produce, and at the same time has an impact on the cost, sales, and profits of the enterprise. Some scholars have carried out relevant research on the impact of freshness-keeping strategies on business operations. Siddh et al. conducted a structured review of the existing literature on the quality of agri-fresh food supply chain. Ma et al. studied the impact of demand information asymmetry on supply chain profits in the three-level supply chain structure where the freshness of fresh produce affects demand. Both quantity and quality loss are viewed as endogenous variables of the freshness-keeping effort, and a coordination contract based on cost and revenue sharing is designed so that all supply chain members can benefit from Pareto improvement. Wang et al. studied the game problem between retailers and farmers in the two-level supply chain. Liu et al. studied the information sharing problem in an E-tailing supply chain for fresh produce with freshness-keeping effort and value-added service. These studies show that freshness-keeping strategies do have an impact on enterprises, but the impacts are different under different business contexts, which need to be studied in combination with specific problems.

Fresh produce are the daily necessities of rigid demand and high frequency consumption. Suppliers and retailers put in more freshness-keeping efforts are driven by consumers’ demand for high freshness. Freshness-keeping efforts are an effective way to reduce loss, but excessive input also leads to increased freshness-keeping costs. Therefore, it is necessary to discuss the post-production freshness-keeping input level for fresh produce by enterprises under the funds constraints. This is the main motivation of our study. To the best of our knowledge, there is no literature research on the optimization of the post-production freshness-keeping input level for fresh produce with the constraints of special funds.

In view of this, the chain transmission of freshness of fresh produce is considered in this paper. Fresh enterprises allocate funds proportionally and decide on the freshness-keeping input of fresh produce in lead time and shelf-life under the special funds constraints. A non-linear programming model of fresh enterprises under the constraints of freshness-keeping costs is established, and the freshness-keeping effort during lead time and shelf-life and subscription are taken as decision variables. Firstly, the optimal freshness-keeping effort level and subscription of the fresh enterprise without the funds constraints are solved to establish a reference benchmark;
Then the funds constraints model of shelf-life freshness-keeping, the funds constraints model of lead time freshness-keeping and the funds constraints model of post-production freshness-keeping are solved in turn, and the optimal freshness-keeping effort, subscription and profits of the fresh enterprise are obtained in the different funds constraints models; Finally, computational experiments are used to analyze the impact of the special funds allocation ratio on the freshness-keeping effort, subscription and profits of the fresh enterprise, providing a reference for the freshness-keeping operation decision-making of fresh enterprises subject to funds constraints.

The contributions of our study can be summarized as follows:(1) an optimal freshness-keeping effort model for fresh produce with the constraints of special funds is proposed. Different from previous studies, the freshness-keeping effort post-production in the whole process including circulation and sales is considered in our model;(2) the research conclusions have a certain marginal contribution to the optimization of post-production freshness-keeping input of fresh produce for enterprises, by analyzing the changes of decision variables and profits through computational experiments.

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature. Section 3 describes the problem, puts forward the corresponding hypothesis, and summarizes the freshness iteration function and the market demand function. Section 4 constructs an optimal freshness-keeping effort model for fresh produce with the constraints of special funds, and analyzes the optimal freshness-keeping decisions of enterprises in different post-production stages. Computational experiments are presented in Section 5 followed by conclusions and future prospects in Section 6.

2. Literature review. In recent years, scholars have begun to pay attention to the operation and management of fresh produce. As the quality of fresh produce decreases, it will not only affect consumer demand, but also cause deterioration loss. So it has become a top priority for fresh produce inventory management to invest in freshness-keeping technology or strengthen freshness-keeping efforts to suppress deterioration, in order to maintain produce quality and reduce quantity loss. Wang and Zhao[36] proposed that manufacturers and retailers should jointly invest in cold chain logistics to reduce the rate of food spoilage, and established a model to solve the optimal investment level of cold chain logistics and product price. Saha et al.[29] used an order level inventory model for deteriorating items with promotional price and trapezoidal-type demand rate to maximize the profits of a retailer, and a modified flower pollination algorithm was applied to find the optimal pricing scheme, freshness-keeping technology investment, and replenishment schedule. Rapolu et al.[28] dealt with the problem of optimizing price, advertisement frequency, freshness-keeping technology investment and ordering policies simultaneously for non-instantaneous deteriorating items whose deterioration rate can be reduced by investing in freshness-keeping technology, while demand depended on both selling price and frequency of advertisement. Liu et al.[18] studied the decision-making problem of whether supermarkets should invest in freshness-keeping technology in an imperfect competitive market environment, and an EOQ model was established to explore the optimal freshness-keeping technology investment and pricing
strategy. Bardhan et al.\cite{2} studied the replenishment and freshness-keeping technology investment strategy of a non-instantaneous deteriorating item with stock-dependent demand. However, the fresh produce mainly realizes the whole cold chain through lead time freshness-keeping and shelf-life freshness-keeping. In the existing literature on post-production freshness-keeping, many scholars have studied the freshness-keeping problems in lead time or shelf-life. Liu et al.\cite{20} constructed an evolutionary game model of logistics outsourcing of fresh enterprises considering lead time freshness-keeping, and found the path to realize the strategy of fresh enterprises and logistics enterprises willing to invest in freshness-keeping efforts. Mohammadi et al.\cite{25} studied the optimal decision-making of lead time freshness-keeping efforts of supply enterprises in the two-level fresh supply chain. Ma et al.\cite{23} considered the transportation of fresh produce through the third-party logistics to reduce loss, and studied the best freshness-keeping efforts made by third-party logistics providers within the lead time. Wang et al.\cite{35} studied the best freshness-keeping efforts of retail enterprises during the shelf-life, in order to improve consumer utility and enterprise performances. Yang\cite{40} discussed the best shelf-life freshness-keeping level of retail enterprises under different sales models. Pattanik et al.\cite{27} proposed an integrated multi-deteriorating item discrete supply chain model to explore the effect of retailers and suppliers’ freshness-keeping efforts during shelf-life. It can be seen from the above literature that existing research has focused on issues related to investment in freshness-keeping technology, but mostly focuses on the produce freshness-keeping in the supply or sales process, and the operation decision-making research on freshness-keeping input from the perspective of the whole process is rarely carried out.

In addition, the freshness-keeping efforts of fresh enterprises in shelf-life and lead time are supported by special funds, which belongs to the decision-making research of enterprises under the funds constraints. At present, most of the literature is the pricing decision-making research of enterprises. Regarding the pricing research of fresh produce, the more common research questions are mainly divided into three aspects: the joint decision-making of fresh produce ordering and pricing, the dynamic pricing strategy of fresh produce, and fresh produce pricing under bundling sales\cite{3, 24}. About the joint decision-making research of fresh produce ordering and pricing, Huang et al.\cite{12} studied a two-level supply chain model for deteriorating items, and two applicable algorithms were designed to determine the optimal production reliability, ordering quantity, and prices. Zhang et al.\cite{42} investigated the joint ordering, pricing, and freshness-keeping problem for perishable products over infinite horizon. From this, a Markov decision process model was proposed, the policy iteration method was adopted to obtain integrated ordering, pricing and freshness-keeping strategies. Zhao et al.\cite{43} studied the retailer’s joint pricing and ordering decisions for a single product in two sales cycles, in order to investigate the single and combined influences of reference effect and quick replenishment policy on the customers’ purchasing behaviors, the retailer’s optimal decisions, and the total profits of two periods. Yang et al.\cite{39} discussed the optimal ordering strategy of retail enterprise and the pricing strategy of manufacturing enterprise in the dual-channel supply chain composed of funds-constrained retail enterprise and manufacturing enterprise. Huang et al.\cite{11} studied the optimal pricing strategies of suppliers, third-party logistics providers, and funds-constrained retailers and the purchasing strategies of retailers under different rights structures. Cao et al.\cite{4} used advance payment and bank loans to solve funds shortage when financial constraints
were imposed on manufacturing enterprises and retail enterprises respectively, and studied the impact of changes in bank interest rates on wholesale and retail prices. About the dynamic pricing strategy, Dong et al.[6] found that dynamic pricing will benefit the enterprise when facing strategic consumers, and the longer the strategic consumers were willing to wait, the higher the price during the price reduction period and the lower the sales volume. Li et al.[14] considered a problem of the dynamic pricing and the periodic ordering for deteriorating items with a stochastic inventory level depending on the stock-dependent demand and the selling price. Herbon et al.[10] studied the optimal dynamic price and inventory decision-making problems of perishable products in which demand depends on price and time, and the inventory level is affected by the demand rate. Wang et al.[37] investigated a joint pricing and inventory problem for a retailer selling fresh-agri products with two-period shelf lifetime in a dynamic stochastic setting. Fan et al.[7] studied the dynamic pricing and replenishment policies of fresh agricultural produce, a dynamic pricing strategy for multi-batch fresh produce that matches real-time freshness was developed and a replenishment policy was established that considers both the freshness and inventory of the previous batch of fresh produce. About pricing under bundling sales, Fang et al.[8] consider the bundle pricing decisions for homogeneous fresh products with quality deterioration. Li et al.[15] found that the use of bundling in combination with dynamic pricing (dynamic bundling) can reduce consumer unfairness perceptions and improve enterprise profitability. Gkgür et al.[9] investigated the question of how dynamic and segment-specific bundle pricing impacts retailer’s revenue. Reviewing the above studies, it is found that scholars pay more attention to fresh produce pricing of enterprises under the freshness-keeping efforts, the cost input of fresh enterprises under the funds constraints are rarely studied.

At present, there has been a wealth of research focused on freshness-keeping efforts and pricing decisions for fresh produce. However, much attention has been paid to the freshness-keeping efforts invested in the supply or sales stage, and the funds constraints of enterprises are often ignored. In fact, enterprises have input freshness-keeping services at all stages of fresh produce reaching consumers from the field. Therefore, this article explores the optimal freshness-keeping input level of the enterprise when post-production freshness-keeping runs through the whole process of produce circulation and sales, under the special funds constraints. And funds are reasonably allocated to make freshness-keeping input decisions during lead time and shelf-life, so as to expand the decision-making research of enterprises under the funds constraints.

3. Problem description and symbolic hypothesis. A enterprise $F$ operating a single fresh produce is considered, which subscribes fresh produce before the sales season and sells the produce to end consumers during the sales season. Let the life cycle of fresh produce be $T$, which is divided into two stages, lead time[13] and shelf-life[46], and the post-production freshness-keeping of fresh produce is divided into lead time freshness-keeping and shelf-life freshness-keeping. As shown in Figure 1, the freshness-keeping sequence process of enterprise $F$ is depicted as following.

(1) Enterprise $F$ receives $Q$ unit fresh produce from the field or factory at time 0, the subscription cost of unit produce is $c$, and then the produce is transported to the sales market;
(2) A freshness-keeping investment should be paid by enterprise F in order to maintain produce freshness. The freshness-keeping input level of enterprise F during the transportation process is denoted as \(e_S\);

(3) After a certain lead time (marked as \(t_S\)), this batch of fresh produce reaches the sales market and is placed on the shelves for sale. At this time, their freshness is \(\theta_S\);

(4) Enterprise F sells this batch of fresh produce at the market price \(p\). The preservation input level of enterprise F during shelf-life is \(e_R\), in order to attract consumers and maintain produce freshness;

(5) Consumers purchase produce according to their freshness \(\theta_R\) during shelf-life (denoted as \(t_R\)). Without loss of generality, suppose \(t_S + t_R = T\).

The cost of freshness-keeping input is needed for lead time and shelf-life. Reference [26] adopted the form of a quadratic cost function, so that the cost of freshness-keeping input in each period is \(B_i = h_i e_i^2/2\), \(h_i > 0\) is the influence coefficient of the freshness-keeping input level in the \(i\)-th period on the freshness-keeping cost, \(i \in \{S, R\}\). \(S, R\) denote the lead time and shelf-life respectively. The initial self-owned funds of the enterprise is \(B\), which allocates special funds between lead time and shelf-life for freshness-keeping according to the ratio of \(\lambda \in (0, 1)\), that is, the special funds constraint is \(h_S e_S^2/2 \leq \lambda B\), \(h_R e_R^2/2 \leq (1 - \lambda)B\). In addition, it is assumed that the retail price \(p\) of fresh produce is an exogenous variable and the residual value and reputation loss of fresh produce are not considered.

3.1. Freshness iteration function. The freshness of fresh produce will gradually decrease over time, but the decrease degree will be affected by the freshness-keeping input. Referring to literature [16], the freshness iteration function of fresh produce is

\[
\theta_j = \theta_{j-1} - (1 - k_j e_j) \eta (t_j/T)^2, j = [1, 2, \ldots, n] \tag{1}
\]

Among them, \(\theta_j\) is the freshness of the fresh produce at stage \(j\), \(\theta_0 = 1\) is the initial freshness of the fresh produce, and \(\eta\) is the natural attenuation extreme value of the fresh produce when there is no freshness-keeping input, \(k_j\) is the sensitivity coefficient of freshness-keeping input to the freshness-keeping input level and \(k_j > 0\). The freshness after freshness-keeping is less than 1, which means that the freshness-keeping input can only slow down the decay rate of produce freshness. In this article, the freshness function of fresh produce after \(e_S\) has been put in fresh-keeping effort in the \(t_S\) time period is:

\[
\theta_S = 1 - (1 - k_S e_S) \eta (t_S/T)^2 \tag{2}
\]

On the basis of putting in freshness-keeping during lead time and shelf-life, the freshness function of the produce purchased by the consumer at the time \(t \in (t_S, T]\)
is:
\[
\theta_{R_t} = 1 - \frac{(1 - k_S e_S) t_S^2 + (1 - k_R e_R) (t - t_S)^2}{T^2} \eta, \ t \in (t_S, T)
\]  
\quad (3)

Naturally, \( \theta_{R_t} \in (0, 1) \), \( \theta_{R_t} \to 0 \) means that fresh produce will not be bought by any consumer. In fact, every consumer has a psychological expectation value related to freshness, and consumers will only buy when \( \theta_{R_t} \) is greater than the expectation value. This article assumes that the psychological expectation value of all consumers is zero in order to simplify the model. It means that as long as fresh produce do not deteriorate to the point of exiting the market, there will always be consumers to buy.

3.2. Market demand function. The market demand for fresh produce is related to the utility of consumers[33, 21], and the utility of consumers is affected by the produce freshness and changes over time, as shown below:
\[
U_t = U_0 + \beta \theta_{R_t}
\quad (4)
\]

Referring to literature [33, 21], \( U_0 \) is the initial utility of consumers on fresh produce, which is a random variable. It obeys the uniform distribution of \([0, 1]\), reflecting the heterogeneity of consumers’ perception to fresh produce. \( \beta \) represents the sensitivity coefficient of consumers to freshness, which obeys the uniform distribution of \([0, 1]\). Consumers will choose to buy when \( U_t > U_0 \), otherwise they will not. Therefore, the market demand for fresh produce at a certain point in time \( t \in (t_S, T] \) is:
\[
D_t = \phi P(U_t > 0) = \phi (1 + \beta \theta_{R_t})
\quad (5)
\]

Among them, \( \phi \) is the potential market size of fresh produce. Therefore, the total market demand \( Q \) is the integral of the time period \((t_S, T] \) [44, 45]:
\[
Q = \int_{t_S}^{T} \phi (1 + \beta \theta_{R_t}) \, dt
\]

Solving the above formula through integral theory, the analytical expression of market demand is obtained as:
\[
Q = \phi (T - t_S) \left( 1 + \frac{1}{3} \beta (2 \theta_S + \theta_{R_T}) \right)
\quad (6)
\]

The symbols used in the article and their meanings are shown in Table 1.

4. Model construction and analysis. The optimal freshness-keeping decision-making of the enterprise in different post-production stages is analyzed by constructing an optimal freshness-keeping effort model for fresh produce with the constraints of special funds.

4.1. Model construction. The freshness-keeping input level \( e_S \) of lead time and the freshness-keeping input level \( e_R \) of shelf-life is given, and the target profits obtained by the enterprise selling \( Q \) units of fresh produce and its constraints are:
\[
\max_{e_S, e_R} \Pi_F (e_S, e_R) = (p - c) \phi (T - t_S) \left( 1 + \frac{1}{3} \beta (2 \theta_S + \theta_{R_T}) \right) - \sum_{i=[S,R]} \frac{h_i e_i^2}{2} \quad (7)
\]

\[
\begin{align*}
\text{s.t.,} & \quad \frac{h_S e_S^2}{2} \leq \lambda B \\
& \quad \frac{h_R e_R^2}{2} \leq (1 - \lambda) B \\
& \quad e_S \in (0, 1) \\
& \quad e_R \in (0, 1)
\end{align*}
\]
Table 1. List of symbols

**Footmark**

$i \in \{S, R\}$, Where $i = S$ represents lead time, $i = R$ represents shelf-life

**Variables**

- $Q$: market demand
- $e_i$: freshness-keeping input level

**Parameters**

- $\lambda$: allocation ratio of lead time for initial funds $B$
- $\beta$: sensitivity coefficient of freshness
- $\eta$: natural attenuation coefficient of fresh produce
- $\phi$: potential market size of fresh produce
- $t_S$: subscribe lead time
- $B$: initial funds of enterprise $F$
- $c$: subscription cost of unit fresh produce
- $p$: market retail price of unit fresh produce
- $B_i$: freshness-keeping input cost at stage $i$
- $k_i$: sensitivity coefficient of freshness-keeping input level to freshness
- $h_i$: sensitivity coefficient of freshness-keeping input level to freshness-keeping cost at stage $i$
- $t_R$: shelf-life of fresh produce
- $\Pi_F$: profit function of enterprise $F$

In formula (7), the objective function is to maximize the profit function $\Pi_C (e_S, e_R)$, in which the first term is the sales profits of fresh produce, and the second term is the sum of the freshness-keeping cost of lead time and shelf-life. The special funds constraints of lead time preservation and shelf-life preservation, as well as the constraints of freshness-keeping input level are included in the constraints. Introducing the Lagrangian multiplier $v_i, i \in \{1, \ldots, 6\}$, the following formula (8)~(11) constitute the KKT condition for solving equation (7).

(a). Original constraints are as following.

\[
\begin{align*}
    g_1 (e_S, e_R) &= \frac{h_S e_S^2}{2} \leq \lambda B \\
    g_2 (e_S, e_R) &= \frac{h_R e_R^2}{2} \leq (1 - \lambda)B \\
    g_3 (e_S, e_R) &= g_4 (e_S, e_R) = e_S \in (0, 1) \\
    g_5 (e_S, e_R) &= g_6 (e_S, e_R) = e_R \in (0, 1)
\end{align*}
\] (8)

(b). Gradient equation is equation (9).

\[
\sum_{i=1}^{6} \nabla g_i (e_S, e_R) v_i = \nabla \Pi_C (e_S, e_R)
\] (9)

(c). Complementary relaxation conditions are as following.

\[
\begin{align*}
    v_1 \left[ \lambda B - \frac{h_S e_S^2}{2} \right] &= 0 \\
    v_2 \left[ (1 - \lambda)B - \frac{h_R e_R^2}{2} \right] &= 0 \\
    v_3 [0 - e_s] &= 0 \\
    v_4 [1 - e_s] &= 0 \\
    v_5 [0 - e_R] &= 0 \\
    v_6 [1 - e_R] &= 0
\end{align*}
\] (10)
(d) Symbolic constraints are as following.

\[
\begin{align*}
    v_i &\geq 0, \quad i \in [1, 2, 4, 6] \\
    v_i &\leq 0, \quad i \in [3, 5]
\end{align*}
\]  

(11)

The Lagrangian multiplier \( v_i = 0, \quad i \in [3, 4, 5, 6] \) is obtained from the original constraints \( e_s \in (0, 1) \) and \( e_R \in (0, 1) \). Next, we discuss the situation where the freshness-keeping input of the enterprise is not subject to funds constraints, which provides a reference for the subsequent analysis.

**Property 1** The optimal freshness-keeping input level \((e_s^*, e_R^*)\) exists and is unique during lead time and shelf-life without funds constraints. The closed-form is:

\[
\begin{align*}
    e_s^* &= \phi \beta \eta (p - c) (T - t_S) \frac{k_s t_s^2}{h_s T^2} \\
    e_R^* &= \frac{1}{3} \phi \beta \eta (p - c) (T - t_S) \frac{k_n (T - t_S)^2}{h_R T^2}
\end{align*}
\]  

(12)

**Proof.** The optimization decision without funds constraints is equivalent to the situation when \( v_1 = v_2 = 0 \). From gradient equation (b), it is obtained that:

\[
\begin{pmatrix}
    \phi (p - c) (T - t_S) \beta \eta \frac{k_s t_s^2}{h_s T^2} - h_s e_s \\
    \frac{1}{3} \phi (p - c) (T - t_S) \beta \eta \frac{k_h (T - t_S)^2}{h_R T^2} - h_R e_R
\end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}
\]  

(13)

The analytical solution of \((e_s^*, e_R^*)\) is shown in formula (12). Because there is no funds constraint on the freshness-keeping input of the enterprise in lead time and shelf-life, that is, its special funds \( B \) can guarantee the establishment of the following formula (14). Therefore, the closed-form shown in formula (12) is the KKT point, that is, \((e_s^*, e_R^*)\) is the optimal freshness-keeping input level of the enterprise.

\[
\begin{align*}
    h_s e_s^2 &\leq \lambda B \\
    \frac{h_R e_R^2}{2} &\leq (1 - \lambda) B
\end{align*}
\]  

(14)

The corresponding freshness-keeping input cost is recorded as \((B_s^*, B_R^*)\) under the optimal freshness-keeping input level \((e_s^*, e_R^*)\). At this time, the optimal subscription and optimal profits of enterprise \( F \) are:

\[
\begin{align*}
    Q^* &= \frac{\phi (T - t_S) (M + 3 h_s h_R T^2 \Delta)}{9 h_s h_R T^4} \\
    \Pi_F^* &= \frac{\beta \eta (p - c) \phi (T - t_S) (M + 6 h_s h_R T^2 \Delta)}{18 \beta \eta \eta h_s h_R T^4}
\end{align*}
\]  

(15)

Among them, \( \Delta = [3 - \beta (\eta - 3)] T^2 + 2 \beta \eta T t_S - 4 \beta \eta t_s^3; \)
\( M = \beta^2 \eta^2 (p - c) \phi (T - t_S) [h_s k_s^2 R^2 (T - t_S)^4 + 9 h_R k_s^2 t_s^4] > 0 \).

Limited by the funds constraints, the initial self-owned funds of the enterprise \( B < B_s^* + B_R^* \) which cannot guarantee that the above formula (15) holds. Therefore, the optimal freshness-keeping level of the enterprise \((e_s^*, e_R^*)\) cannot be reached under the funds constraints.

**4.2. Model analysis.** The enterprise can adjust the parameter \( \lambda \) to flexibly allocate funds \( B \) to the lead-time preservation or shelf-life preservation. Next, the optimal decision-making of freshness-keeping input level is analyzed in three cases: funds constraints of shelf-life freshness-keeping, funds constraints of lead time freshness-keeping, and funds constraints of both stages. These three situations correspond to \( v_1 = 0, v_2 \neq 0, v_1 \neq 0, v_2 = 0 \) and \( v_1 \neq 0, v_2 \neq 0 \) in turn, responding to the situation of \( v_1 = v_2 = 0 \) in the previous article.
4.2.1. Analysis on the funds constraints model of shelf-life freshness-keeping. The enterprise $F$ preferentially allocates special funds to guarantee the freshness-keeping input in lead time among the initial self-owned funds $B$, that is, $\lambda B \geq B^*_S$, and the freshness-keeping input costs of shelf-life $(1 - \lambda)B$ is lower than $B^*_R$. Let $(e^*_S, e^*_R)$ be the two-stage optimal freshness-keeping input level of the enterprise under special funds constraints of shelf-life freshness-keeping. Property 2 shows the closed-form of $(e^*_S, e^*_R)$.

**Property 2** The optimal freshness-keeping input level $(e^*_S, e^*_R)$ exists and is unique during lead time and shelf-life under the funds constraints of shelf-life freshness-keeping. The closed-form is:

$$
\begin{align*}
\begin{cases}
  e^*_S &= \phi \beta \eta (p - c)(T - t_S) \frac{k_1 t_s^2}{h_S} \\
  e^*_R &= \sqrt{\frac{2(1 - \lambda)B}{h_R}}
\end{cases}
\end{align*}
$$

Proof. The special funds constraints of shelf-life freshness-keeping means that $v_1 = 0, v_2 \neq 0$ are established. Then $(1 - \lambda)B - \frac{h_B e^*_R}{2} = 0$ is obtained from the complementary relaxation condition (c), and the optimal freshness-keeping input level in shelf-life of the enterprise $e^*_S = \sqrt{\frac{2(1 - \lambda)B}{h_R}}$ can be obtained. From gradient equation (b), it is obtained that:

$$
\begin{align*}
\begin{pmatrix}
  \phi(p - c)(T - t_S) \beta \eta \frac{k_1 t_s^2}{h_S} - h_S e_S \\
  \frac{1}{2} \phi(p - c)(T - t_S) \beta \eta \frac{k_1 (T - t_s)^2}{h_R} - h_R e_R
\end{pmatrix} = 
\begin{pmatrix}
  0 \\
  h_R e_R
\end{pmatrix}
\end{align*}
$$

Solve simultaneously and bring in $e^*_R$ to get:

$$
\begin{align*}
\begin{cases}
  e^*_S &= \phi \beta \eta (p - c)(T - t_S) \frac{k_1 t_s^2}{h_S} \\
  v^*_2 &= \frac{4 \phi \beta \eta (p - c)(T - t_S) \frac{k_1 (T - t_s)^2}{2h_R}}{2(1 - \lambda)B} - 1
\end{cases}
\end{align*}
$$

Since $\frac{h_B e^*_R}{2} > (1 - \lambda)B$ can get $v^*_2 \geq 0$, this satisfies the symbol constraint (d). Therefore, $(e^*_S, e^*_R)$ is the KKT point of formula (7), that is, $(e^*_S, e^*_R)$ is the optimal freshness-keeping input level of the enterprise.

Under the funds constraints of shelf-life freshness-keeping, the optimal subscription and optimal profits of the enterprise $F$ are:

$$
\begin{align*}
\begin{cases}
  Q^*_1 = \phi(T - t_S) \left\{ 1 + \beta - \frac{\beta \eta (1 - \lambda)B (T - t_s) + 3t^*_S(1 - e^*_S)}{3T} \right\} \\
  \Pi^*_F = (\lambda - 1)B - \frac{\beta^2 h^2 (c - p)^2}{2h_S T} T^*_S + (p - c)Q^*_1
\end{cases}
\end{align*}
$$

4.2.2. Analysis on the funds constraints model of lead time freshness-keeping. The enterprise $F$ preferentially allocates special funds to guarantee the freshness-keeping input in shelf-life in the funds constraints model of lead time freshness-keeping, that is, $(1 - \lambda)B \geq B^*_R$. The freshness-keeping input costs of lead time $\lambda B$ is lower than $B^*_R$. Let $(e^*_S, e^*_R)$ be the optimal freshness-keeping input level of the enterprise under the special funds constraints of lead time freshness-keeping. Property 3 shows the closed-form of $(e^*_S, e^*_R)$.

**Property 3** The optimal freshness-keeping input level $(e^*_S, e^*_R)$ exists and is unique during lead time and shelf-life under the funds constraints of lead time.
freshness-keeping. The closed-form is:

\[
e^*_S = \sqrt{\frac{2\lambda B}{h_S}}
\]

(20)

Proof. The special funds constraints of lead time freshness-keeping means that \( v_1 \neq 0, v_2 = 0 \) are established. Then \( \lambda B - \frac{h_S e^*_S}{2} = 0 \) is obtained from the complementary relaxation condition (c), and \( e^*_S = \sqrt{\frac{2\lambda B}{h_S}} \) can be obtained. From gradient equation (b), it is obtained that:

\[
\begin{align*}
\frac{\phi(p-c)(T-t_S)\beta\eta h_S}{\sqrt{\theta h_S \lambda B}} - h_S e^*_S & = 0 \\
\frac{1}{2} \frac{\phi(p-c)(T-t_S)\beta\eta h_S^2}{h_R t^2} & = 0
\end{align*}
\]

(21)

Solve simultaneously and bring in \( e^*_S \) to get:

\[
\begin{align*}
e^*_R & = \frac{1}{2} \frac{\phi(p-c)(T-t_S)\beta\eta h_S^2}{h_R t^2} \\
v_1 & = \frac{\phi(p-c)(T-t_S)\beta\eta h_S^2}{\sqrt{\theta h_S \lambda B}} - 1
\end{align*}
\]

(22)

Since \( \frac{h_S e^*_S}{2} > \lambda B \) can get \( v^*_1 \geq 0 \), this satisfies the symbol constraint (d). Therefore, \( (e^*_S, e^*_R) \) is the KKT point of formula (7), that is, \( (e^*_S, e^*_R) \) is the optimal freshness-keeping input level of the enterprise.

Under the funds constraints of lead time freshness-keeping, the optimal order quantity and optimal profits of the enterprise F are:

\[
\begin{align*}
Q^*_2 & = \phi(T-t_S) \left\{ 1 + \beta - \frac{\beta \eta [1-k_R e^*_S(T-t_S)^2] - 3\beta \eta (-1+k_R e^*_S)]}{\lambda B} \right\} \\
\Pi^*_2 & = -\lambda B + \frac{\phi(p-c)(T-t_S)\beta^2 \sigma^2 (c-p) \phi(T-t_S)^2 + 6b_R T^2 [-\Delta - 3\beta \eta h_S e^*_S e^*_R]}{18b_R T^2}
\end{align*}
\]

(23)

4.2.3. Analysis on the funds constraints model of post-production freshness-keeping.

The enterprise F allocates special funds according to the ratio \( \lambda \) for freshness-keeping input in lead time and shelf-life in the funds constraints model of post-production freshness-keeping. However, there are funds constraints on the freshness-keeping input in these two stages, that is, \( \lambda B < B^*_S, (1-\lambda)B < B^*_R \). Let \( (e^*_S, e^*_R) \) be the optimal freshness-keeping input level of the enterprise under the special funds constraints of post-production freshness-keeping. Property 4 shows the closed-form of \( (e^*_S, e^*_R) \).

**Property 4** The optimal freshness-keeping input level \( (e^*_S, e^*_R) \) exists and is unique during lead time and shelf-life under the funds constraints of post-production freshness-keeping. The closed-form is:

\[
\begin{align*}
e^*_S & = \sqrt{\frac{2\lambda B}{h_S}} \\
e^*_R & = \sqrt{\frac{2(1-\lambda)B}{h_R}}
\end{align*}
\]

(24)

Proof. The special funds constraints of post-production freshness-keeping means that \( v_1 \neq 0, v_2 \neq 0 \) are established. Then \( \lambda B - \frac{h_S e^*_S}{2} = 0, (1-\lambda)B - h_R e^*_R = 0 \) are obtained from the complementary relaxation condition (c), and \( e^*_S = \sqrt{\frac{2\lambda B}{h_S}}, e^*_R = \sqrt{\frac{2(1-\lambda)B}{h_R}} \).
\[ \sqrt{\frac{2(1-\lambda)B}{h_R}} \] can be obtained. From gradient equation (b), it is obtained:
\[ \begin{aligned}
    \left( \phi(p-c)(T-t_s) \beta \eta \frac{k_{st}^2}{2} - h_S e_S \right) &= \left( h_S e_S \right) v_1 + \left( 0 \right) v_2 \\
    \frac{1}{2} \phi(p-c)(T-t_s) \beta \eta \frac{k_{st}(T-t_s)^2}{T^2} - h_R e_R &= \left( 0 \right) v_1 + \left( h_R e_R \right) v_2
\end{aligned} \]
(25)

Solve simultaneously and bring in \( e_{S2}^* \) to get:
\[ \begin{aligned}
    v_1^* &= \frac{\phi(p-c)(T-t_s) \beta \eta \frac{k_{st}^2}{2}}{\sqrt{2h_S \lambda B}} - 1 \\
    v_2^* &= \frac{\frac{1}{2} \phi(p-c)(T-t_s) \beta \eta \frac{k_{st}(T-t_s)^2}{T^2}}{\sqrt{2h_S (1-\lambda) B}} - 1
\end{aligned} \]
(26)

Since \( \frac{h_S e_{S2}^2}{2} > \lambda B, \frac{h_R e_{R2}^2}{2} > (1-\lambda)B \) can get \( v_1^* \geq 0, v_2^* \geq 0 \), this satisfies the symbol constraint (d). Therefore, \((e_{S3}^*, e_{R3}^*)\) is the KKT point of formula (7), that is, \((e_{S3}^*, e_{R3}^*)\) is the optimal freshness-keeping input level of the enterprise.

Under the funds constraints of post-production freshness-keeping, the optimal order quantity and optimal profits of the enterprise \( F \) are:
\[ \begin{aligned}
    Q_3^* &= \phi(T-t_s) \left\{ 1 + \beta - \frac{\beta \eta [1-k_{st}^{-E}] (T-t_s)^2-3T^2(-1+k_{st}^{-E})]}{3T^2} \right\} \\
    \Pi_{F3}^* &= -B + \lambda + (p-c)Q_3^*
\end{aligned} \]
(27)

5. Numerical calculation and analysis. The initialization parameters are as follows: \( \phi = 100, \beta = 0.2, \eta = 10 \), other parameters are: \( c = 1, p = 3, h_S = 50, h_R = 60, k_S = 1.2, k_R = 1.1, T = 1, t_s = 0.3 \). The optimal freshness-keeping input level and freshness-keeping input costs of the enterprise without funds constraints are calculated according to the above parameter assignment, as shown in Table 2.

| \( e_{S3}^* \) | \( e_{R3}^* \) | \( B_{S3}^* \) | \( B_{R3}^* \) | \( Q^* \) | \( \Pi_{F3}^* \) |
|---|---|---|---|---|---|
| 0.6048 | 0.8384 | 9.1446 | 21.0897 | 78.7676 | 127.3009 |

Assuming that initial self-owned funds of the enterprise \( B < B_{S3}^* + B_{R3}^* = 30.2343 \), Table 3 shows the optimal value under which the enterprise allocates special freshness-keeping funds according to different \( \lambda \) when \( B = 25 \), and the corresponding change trend of these optimal values is shown in Figure 2. It can be seen from Table 3 that when \( \lambda = 0.3 \), the enterprise obtains the largest profits. At this time, the special funds allocated to lead time freshness-keeping is 7.5, and the special funds allocated to shelf-life freshness-keeping is 17.5. We can see that the freshness-keeping input of lead time and shelf-life are both limited by the funds constraints, comparing with Table 2.

Table 4 shows the optimal decision under different initial self-owned funds of the enterprise. The change trend of the optimal decision value of the enterprise with self-owned funds \( B \) is shown in Figure 3. It can be seen from the figure that the allocation ratio of the special funds is almost constant, that is, 30\% of its self-owned funds \( B \) will be allocated to the lead time freshness-keeping input, and the remaining 70\% of the funds will be allocated to the shelf-life freshness-keeping input. At the same time, we can also see that all the optimal decision values of the enterprise
Figure 2. The change trend of the optimal value under different allocation ratios $\lambda$ when initial self-owned funds $B = 25$

Table 3. The optimal value under different allocation ratios $\lambda$ when initial self-owned funds $B = 20$, $j = [1, 2, 3]$

| $\lambda$ | $e^*_Sj$ | $e^*_Rj$ | $Q^*$ | $\Pi^*_F$ |
|-----------|----------|----------|-------|----------|
| 0.1       | 0.3162   | 0.8384   | 74.4044 | 125.2191 |
| 0.2       | 0.4472   | 0.8165   | 75.8328 | 126.6656 |
| 0.3       | 0.5477   | 0.7638   | 76.0261 | 127.0521 |
| 0.4       | 0.6048   | 0.7071   | 75.4640 | 126.7834 |
| 0.5       | 0.6048   | 0.6455   | 73.9143 | 126.1841 |
| 0.6       | 0.6048   | 0.5774   | 72.2002 | 125.2558 |
| 0.7       | 0.6048   | 0.5000   | 70.2546 | 123.8646 |
| 0.8       | 0.6048   | 0.4082   | 67.9467 | 121.7489 |
| 0.9       | 0.6048   | 0.2887   | 64.9391 | 118.2335 |

are increasing with the increase of initial self-owned funds $B$, but they are all lower than the optimal value without the funds constraints.

Table 4. The optimal decision of the enterprise when initial self-owned funds $B$ changes, $j = [1, 2, 3]$

| $B$ | $e^*_Sj$ | $e^*_Rj$ | $Q^*$   | $\Pi^*_F$ |
|-----|----------|----------|---------|----------|
| 5   | 0.2454   | 0.3413   | 60.8285 | 116.6570 |
| 10  | 0.3470   | 0.4827   | 65.9213 | 121.8426 |
| 15  | 0.4250   | 0.5912   | 69.8292 | 124.6583 |
| 20  | 0.4907   | 0.6826   | 73.1236 | 126.2473 |
| 25  | 0.5477   | 0.7638   | 76.0261 | 127.0521 |
| 30  | 0.6010   | 0.8361   | 78.6502 | 127.3004 |
6. **Conclusion and future research.** In this paper, the freshness-keeping input level and subscription are used as decision-making variables to study the optimal decision-making problem of the fresh enterprise with the constraints of preservation funds. Market demand is closely related to the freshness-keeping input level of both parties in the supply chain. The freshness-keeping effort and subscription under no funds constraints, funds constraints of shelf-life freshness-keeping, funds constraints of lead time freshness-keeping, and funds constraints of post-production freshness-keeping are successively solved, through mathematical analysis and related theories of non-linear programming. And the changes of decision variables and profits are analyzed through computational experiments. The research conclusions are as follows:

Firstly, the enterprise can adjust the allocation ratio to allocate special funds. The allocation ratio can be adjusted by the enterprise to prioritize the freshness-keeping input in shelf-life or lead time, according to business needs. Therefore, it is divided into the funds constraints model of shelf-life freshness-keeping, the funds constraints model of lead time freshness-keeping and the funds constraints model of post-production freshness-keeping in the funds constraints model. Secondly, the optimal decision in different models exists and is unique. The optimal freshness-keeping effort and subscription of the fresh enterprise under the special funds constraints exist and are unique, but they cannot reach the optimal level of freshness-keeping effort without the funds constraints. Thirdly, the sensitivity of the funds allocation ratio to optimal decision-making. The profits and subscription of the fresh enterprise first increase and then decrease with the increase of the allocation ratio, and obtain the maximum profits when $\lambda = 0.3$. The special funds for freshness-keeping during lead time (shelf-life) increase (decrease), as the allocation ratio increases. At the same time, the freshness-keeping effort during lead time first increases but finally tends to level off, and the freshness-keeping effort during shelf-life decreases accordingly. Therefore, the fresh enterprise can reduce the impact of
the funds constraints on business operations and maximize profits by reasonably adjusting the funds allocation ratio.

The above conclusions bring certain theoretical references to decision makers of the fresh enterprise subject to the funds constraints, but there are supply and demand risks in fresh produce. The issue of supply and freshness-keeping of fresh produce from the perspective of supply chain is of great significance. Therefore, the inventory and freshness-keeping decision-making and coordination issues of the fresh produce supply chain under the funds constraints will be considered in the future research. In addition, the use of financing means to solve funds shortage is a routine operation of the enterprise. The impact of enterprise financing strategies on freshness-keeping technology input will be considered, and the difference between internal financing and external financing of the supply chain will be compared in the follow-up research.

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E-mail address: bingzhou@ctbu.edu.cn
E-mail address: 2019651916@email.ctbu.edu.cn
E-mail address: Xin_f@ctbu.edu.cn