Pricing of fresh agricultural product supply chain under transportation interruption

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Abstract: With the trend of global economic integration and the improvement of logistics, transportation, and storage technology, regional restrictions on the sales of fresh agricultural products have gradually decreased. At the same time, due to traffic accidents, natural disasters, and other factors, the possibility of interruption in the transportation supply chain of fresh agricultural products has been increased. This article examines a three-level fresh supply chain with the possibility of transportation interruption. The Stackelberg method is used to solve the equilibrium solution, and the results under centralized and decentralized models are analyzed. We found that the increase in the probability and duration of transportation interruptions actually leads to less investment by distributors in cold chain services, resulting in increased profits for retailers and decreased profits for distributors and manufacturers.

1. Introduction
Fresh agricultural products have a short life cycle, are prone to decay, and customers have high requirements for their freshness. The freshness of agricultural products will directly affect consumers' willingness to purchase and bring direct economic losses to enterprises. A constant low temperature state can effectively prevent the deterioration and decay of fresh agricultural products, and cold chain logistics transportation has become a necessary choice for fresh agricultural product enterprises.

This article studies the transportation interruption probability of two product transfer stages in a three-level supply chain, and the cold chain can reduce the negative impact of interruption time on goods to a certain extent. Therefore, this article studies the investment and pricing issues of supply chain members on the cold chain level under the possibility of interruption.

2. Literature Review
The perishable nature of fresh products also adds complexity to the fresh supply chain, and there are many scholars studying the supply chain of fresh agricultural products both domestically and internationally. In terms of decision-making in the fresh supply chain, Wang M et al.[1] studied the optimal investment level of cold chain and advertising in fresh supply chain. He Y et al.[2] analyzed the impact of using blockchain technology (BCT) on the pricing decisions and profits of supply chain members. Ma X et al.[3] considered information asymmetry in the tertiary fresh agricultural product supply chain. Unlike the above literature, this article considers a three-level fresh agricultural product supply chain and considers supply chain disruptions. Many scholars have also conducted research on supply chain disruptions. Gupta V et al.[4] studied a secondary supply chain where a supplier may face disruptions and demonstrated that early sales can mitigate the impact of supply disruptions. Moon I et al.[5] studied investment decisions in the supply chain of fresh agricultural products and found that incremental quantity discount contracts could maximize the efficiency of manufacturers and retailers. Transportation interruption is also a type of supply interruption, and this article focuses on transportation interruption.

Therefore, this article will consider the probability and duration of transportation interruption based on previous research, and analyze the impact of interruption probability and interruption time on equilibrium decision-making and profits.

3. Model Description and Symbol Introduction
This article considers a three-level fresh agricultural product supply chain consisting of manufacturers, distributors, and retailers. The manufacturer produces fresh agricultural products and sells them to various retailers through distributors, and ultimately the retailers sell the products to consumers. The interruption probability between each node in the supply chain is $n$, and the interruption duration $t_o$ is a fixed quantity. Manufacturers produce products at unit cost $c$, and the unit transportation cost and cold chain service cost of the products from the manufacturer to the distributor are $c_v$ and $c_s$, respectively. The total cost is

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borne by the distributor. The distributor considers product loss and transportation cost and provides products to the retailer at wholesale price $w_d$. The transportation cost and cold chain service cost are borne by the retailer. Finally, Retailers sell products to the market at selling price $p$. The level of service cost $e \in [0, 1]$ has a significant impact on the quality loss of fresh agricultural products, making $\lambda$ as service cost factor, $c_s = k/e^2/2$.

Referring to the description of the freshness of fresh agricultural products in existing literature, the freshness function of fresh agricultural products is defined as $\theta(t) = e \eta (1 - e^n)^2, \theta \geq 0, t \in \{0, T\}$, where $\eta > 0$ is the sensitivity coefficient of freshness to time, $t_i$ is the total transportation time of the product, and $T$ represents the entire lifecycle of the product. $D$ representing the random market demand, the market demand function is $D = k - bp + \beta \theta$, where $k$ is the potential size of the fresh agricultural product market, $b(b > 0)$ is the consumer price sensitivity coefficient, and $\beta(\beta > 0)$ is the consumer freshness sensitivity coefficient.

When there is no interruption in both stages of transportation in the supply chain, the product transportation time is $2t$; When one of the road sections is interrupted, the product transportation time is $2t + t_o$; When both stages of transportation are interrupted, the transportation time of the product is $2t + 2t_o$, and the expected transportation time of the supply chain is:

$$E[t] = 2t(1 - n)^2 + 2n(1 - n)(2t + t_o) + n^2(2t + 2t_o) = 2nt_o + 2t$$

Therefore, within a sales period $T$, the expected order quantity of the product is:

$$Q = k - bp + \beta E[t]$$

$$= k - bp + \beta \left( e \eta \left( 1 - \left( \frac{2nt_o + 2t}{T} \right)^2 \right) \right)$$

Assuming conditions:

1. For the convenience of calculation, it is assumed that the transportation time from the manufacturer to the distributor and the transportation time from the distributor to the retailer are both $t$.
2. Assuming that all decision-makers are risk neutral, their pursuit is to maximize their respective profits.
3. Assuming that fresh products are completely fresh when transported from the manufacturer until they are loaded onto the vehicle, quality degradation begins, and the sales time after the fresh products arrive at the retailer is not considered.
4. To ensure the profitability of all parties in the supply chain, it is necessary to meet the requirements $c < w_m < w_d < p$.

The symbol definitions of the relevant variables in the model are shown in Table 1:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Probability of supply chain transportation interruption</td>
</tr>
<tr>
<td>$c$</td>
<td>Production cost of fresh products</td>
</tr>
<tr>
<td>$c_v$</td>
<td>Transportation cost</td>
</tr>
<tr>
<td>$c_s$</td>
<td>Cold chain service cost</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Service cost factors</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Sensitivity coefficient of freshness to time</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Freshness of fresh products</td>
</tr>
<tr>
<td>$t$</td>
<td>Transportation time between two nodes</td>
</tr>
<tr>
<td>$t_o$</td>
<td>Interrupt duration</td>
</tr>
<tr>
<td>$Q$</td>
<td>Product order quantity</td>
</tr>
<tr>
<td>$k$</td>
<td>Potential market size</td>
</tr>
<tr>
<td>$p$</td>
<td>Consumer price sensitivity coefficient</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Sensitivity coefficient of consumer freshness</td>
</tr>
</tbody>
</table>

### Decision variables

| $p$ | Product sales price |
| $e$ | Cold chain service level |
| $w_d$ | Wholesale prices for distributors |
| $w_m$ | Wholesale prices of manufacturers |

### Profit function

| $\pi_{SC}$ | Supply Chain Profit |
| $\pi_d$ | Distributor profit |
| $\pi_r$ | Retailer profit |
| $\pi_m$ | Manufacturer's profit |

### 4. Concentration and dispersion

#### 4.1. Centralized decision-making

The supply chain model under centralized decision-making serves as the benchmark model, and the expected profit function of the supply chain is:

$$\pi_{SC} = Q(p - c - 2c_v) - 2c_s$$

The centralized supply chain needs to determine sales price $p$ and cold chain service level $e$ to achieve the maximum overall profit of the supply chain. Calculate the second derivative of $p$ from equation (3) to obtain $\frac{\partial^2 \pi_{SC}}{\partial p^2} = -2b < 0$, and calculate the second derivative of $e$ to obtain $\frac{\partial^2 \pi_{SC}}{\partial e^2} = -2\lambda < 0$. The optimal sales price and cold chain service level under the centralized decision-making model can be obtained by making $\frac{\partial \pi_{SC}}{\partial p} = 0$ and $\frac{\partial \pi_{SC}}{\partial e} = 0$:

$$p_{SC} = \frac{bc + k + e\beta \eta - A\beta \eta + 2bc_v}{2b}$$

$$e_{SC}^* = \frac{(1 - A)\beta \eta (p - c - 2c_v)}{2\lambda}$$

Where $A = \frac{(2t + 2nt_o)^2}{T^2}$, to ensure that the supply chain is profitable, $4b\lambda - (A - 1)^2\beta^2\eta^2 > 0$ needs to be met.
4.2. Optimal Decision Making in Decentralized Decision Models

The decision-making order in a decentralized model is: 1) Manufacturers determine wholesale prices \( w_m \). 2) Distributors determine wholesale prices \( w_d \) and cold chain service levels. 3) Retailers determine the selling price. The following is the solution process using the reverse recursive method.

The expected profit for retailers is:

\[
\pi_r = Q(p - w_d - c_v) - c_s \tag{6}
\]

Calculate the second derivative of \( p \) to obtain \( \frac{\partial^2 \pi_r}{\partial p^2} = -2b < 0 \), so that \( \frac{\partial \pi_r}{\partial p} = 0 \) can obtain the optimal sales price that \( p^* \) satisfies:

\[
p^* = \frac{bw_d + k + e\beta \eta - Ae\beta \eta + bc_v}{2b} \tag{7}
\]

The expected profit function of distributors is:

\[
\pi_d = Q(w_d - w_m - c_v) - c_s \tag{8}
\]

Distributors need to determine the level of cold chain service \( e \) and wholesale prices \( w_d \) for retailers. Substitute \( p^* \) into \( \pi_d \) and calculate the second-order derivatives of \( e \) and \( w_d \) for \( \pi_d \) respectively to obtain:

\[
\frac{\partial^2 \pi_d}{\partial e^2} = -\lambda < 0 \quad \frac{\partial^2 \pi_d}{\partial w_d^2} = -b < 0 , \text{ so that the first-order derivative is equal to } 0:
\]

\[
e^* = \frac{(\beta \eta - A\beta \eta)(w_d - w_m - c_v)}{2\lambda} \tag{9}
\]

\[
w_d^* = \frac{k + bw_m + e\beta \eta - Ae\beta \eta}{2b} \tag{10}
\]

The expected profit function of the manufacturer is:

\[
\pi_m = Q(w_m - c) \tag{11}
\]

Substituting \( e^* \) into \( \pi_m \) to obtain the second derivative of \( w_m \). yields:

\[
\frac{\partial^2 \pi_m}{\partial w_m^2} = \frac{2b^3 \lambda}{(\lambda - 1)^2 \beta \eta^2 - 2b\lambda} < 0 \text{, so } \pi_m \text{ is the concave function of } w_m, \text{ and the optimal decision is obtained:}
\]

\[
w_m^* = \frac{bc + k - 2bc_v}{2b} \tag{12}
\]

4.3. Analysis of Equilibrium Results

Theorem 1: \( e^*, e_{SC}, p^*, p_{SC}, w_d^*, \pi_{SC}, \pi_r^*, \pi_m^* \) and \( \pi_m^* \) all decrease with increasing.

Theorem 1 indicates that if consumers’ sensitivity to the price of fresh products increases, retailers will inevitably lower their sales prices in order to increase sales volume, and wholesale prices will also decrease accordingly. At this time, distributors will reduce cost expenditures by reducing the cold chain service level based on the principle of maximizing profits. The freshness of fresh products will quickly decrease, and the market will experience a vicious cycle of "low quality and low price". However, the increase in demand stimulated by a decrease in sales prices is lower than the decrease in demand caused by a decrease in freshness, ultimately resulting in a decrease in profits for retailers, distributors, manufacturers, and the overall supply chain.

Theorem 2: \( e^*, e_{SC}, p^*, p_{SC}, w_d^*, \pi_{SC}, \pi_m^* \) all increase with increasing, while \( \pi_r^* \) decreases with increasing \( \beta \).

Theorem 2 indicates that when consumers value the freshness of products more, distributors will increase their investment to improve the level of cold chain services. In order to fill the increased costs, wholesale prices will also increase, and retailers will increase their sales prices to maximize profits. From this perspective, the increase in consumer freshness sensitivity will bring a positive situation of "high quality and high price" to the market, avoiding the occurrence of vicious price wars. For distributors and manufacturers, the positive impact of increased freshness sensitivity on market demand is greater than the negative impact of increased sales prices suppressing demand.

Theorem 3: \( e^*, e_{SC}, p^*, p_{SC}, w_d^*, \pi_{SC}, \pi_m^* \) are all substantive functions related to interrupt probability \( n \) and interrupt time \( t_0 \). However, \( \pi_r^* \) is an increasing function related to interrupt probability \( n \) and interrupt time \( t_0 \).

The result shown in Theorem 3 is that \( e^* \) and \( e_{SC} \) decrease as \( n \) and \( t_0 \) increase. This is because the increase in \( n \) and \( t_0 \) is an increase in risk for the supply chain and its members, and the negative impact is also increasing. Choosing to lower the cold chain service level by distributors not only saves costs, but also provides consumers with lower sales prices to attract more consumers, thereby alleviating the shrinking demand caused by the accelerated loss of freshness. For retailers, the increase in interruption probability and interruption time brings the dividend of lower wholesale prices. Although demand has decreased, overall profits have increased.

5. Example analysis

To verify the correctness of the above conclusion, a numerical example analysis was conducted by setting parameters. The specific values of the relevant parameters are set as shown in Table 2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>8.5</td>
</tr>
<tr>
<td>( \beta )</td>
<td>1.5</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.5</td>
</tr>
<tr>
<td>( t_0 )</td>
<td>10</td>
</tr>
<tr>
<td>( T )</td>
<td>80</td>
</tr>
<tr>
<td>( k )</td>
<td>1000</td>
</tr>
<tr>
<td>( b )</td>
<td>50</td>
</tr>
<tr>
<td>( \beta )</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 2 The specific values of the relevant parameters
Figures 1, 2, 3, and 4 respectively show the impact of interruption probability and interruption time on the overall profit of the supply chain, retailers, distributors, and manufacturers. From the graph, it can be seen that the profit of retailers increases with the increase of interruption probability and interruption time, and the larger the interruption probability and interruption time, the smoother the profit increase. The overall profit of the supply chain, distributors, and manufacturers decreases with the increase of interruption probability and interruption time, and the larger the interruption probability and interruption time, the faster the profit decreases. Comparing the coordinate spans of $\pi_{SC}^*$, $\pi_{d}^*$, and $\pi_{m}^*$, it can be seen that although retailers' profits are on the rise, the increase effect is not significant, and manufacturers' profits have decreased more significantly than distributors.

6. Conclusion

This article studies a three-level fresh agricultural product supply chain consisting of a manufacturer, a distributor, and a retailer. It considers the possibility of unexpected interruptions on two transportation routes and the impact of interruption duration, and designs reasonable contracts to coordinate the supply chain. The following conclusion can be drawn: (1) The more consumers pay attention to the freshness of fresh products, the positive effect it has on the good situation of "high quality and high price" in the market. However, the more consumers pay attention to the price of fresh products, the more "low price and low quality" products will appear in the market. (2) When the probability and duration of interruption increase, distributors will avoid greater losses by reducing the cold chain service level, and retailers' profits will increase slightly, while distributors and manufacturers' profits will decrease.

Based on the above conclusions, this article draws the following management inspiration: to strengthen consumers' demand for high freshness of fresh products and lay a solid foundation for a healthy market cycle; Enterprises should fully consider unexpected interruptions and interruption times that may occur in the supply chain in their operational management, and make scientific and reasonable decisions; Strengthen cooperation among supply chain members, integrate resources from all parties, and achieve mutual benefit. However, this article only considers the quality loss of fresh products over time, and in the future, the quantity consumption of fresh products can be considered simultaneously. The length of interruption time has a significant impact on their quality loss. In addition, this article only considers the coordination situation of a single manufacturer, a single distributor, and a single retailer, so future research can consider the situation where there are multiple enterprises in the supply chain node.
References


