Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 12, No. 2, 2023

Research on the Network Equilibrium of Fresh Agricultural Product Supply Chain with Third Party Logistics Participation in Decision Making

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Abstract: Introducing Third-party logistics into the supply chain of fresh agricultural products can reduce the logistics cost of the supply chain and improve the freshness and quality of fresh agricultural products. Taking the fresh agricultural product supply chain network, which includes three decision-making entities: fresh agricultural product suppliers, 3PL service providers, and retailers, as the research object, a fresh agricultural product supply chain network equilibrium model is constructed using variational inequality theory. The impact of 3PL service providers' logistics service level on their equilibrium transaction volume and overall profit is studied. The research results show that when Third-party logistics is involved in the supply chain of fresh agricultural products, considering the logistics service level of 3PL service providers, with the improvement of service level, the overall profit of the supply chain of fresh agricultural products increases. It is a beneficial attempt to realize the profit of the supply chain of fresh agricultural products to improve the freshness and quality of fresh agricultural products through Third-party logistics; When the logistics service level rises to a certain level, and the service level continues to improve, the overall profit growth of the supply chain decreases. It is necessary to improve the impact of logistics service level on the freshness and quality of fresh agricultural products through other forms.

Keywords: Fresh agricultural product supply chain, Third-party logistics, Network equilibrium, Variational inequality.

1. Introduction

Fresh agricultural products play a crucial role in our daily lives. As an important component of the agricultural industry chain, fresh agricultural products are an important foundation for ensuring national food security. Fresh agricultural products belong to the category of time sensitive products with diminishing utility, and there is a certain proportion of product loss over time[1]. The supply chain network equilibrium of fresh agricultural products takes fresh agricultural products as the research object, considers the characteristics of agricultural products themselves over time, and establishes a supply chain network model using variational inequality theory to find the equilibrium price and equilibrium transaction volume on the fresh agricultural product supply chain. The loss rate of fresh agricultural products in China during the circulation process is much higher than that of developed countries, which means that there are still many problems to be solved in the supply chain network of fresh agricultural products in China.

The circulation pattern of fresh agricultural products in China is constantly evolving, with traditional and modern models constantly interacting, replacing, and integrating. The single circulation model is gradually becoming diversified[2]. With the improvement of cold chain logistics productivity, the level of cold chain logistics services has also increased, bringing more profits to all parties in the supply chain[3]. The third-party logistics industry, as a new type of logistics service format emerging in the context of business outsourcing and high demand for enterprise logistics, can better reflect the level of cold chain logistics services[4]. In response to the risks caused by the inherent attributes of fresh agricultural products, enterprises have outsourced a series of logistics services to third-party logistics enterprises, thereby focusing on their core business development[5]. Both users and providers of TPL services must be equipped with the best products in terms of strategy, processes, and technology[6]. Improving logistics optimization and integrating the entire supply chain through third-party logistics to achieve supply chain transformation is also another important way in the future. Therefore, this study considers introducing third-party logistics service providers as the main participants in the fresh agricultural product supply chain to optimize the existing network structure of the fresh agricultural product supply chain.

The current research on fresh agricultural product supply chain decision-making involves income sharing contracts [7], revenue sharing contracts [8], cost sharing contracts [9], and other aspects. Third party logistics service providers can play an important role in agricultural product supply chain management to improve customer satisfaction and reduce supply chain management costs [10]. When third-party logistics participates in the supply chain of fresh agricultural products, introducing logistics service cost sharing contracts and logistics service quantity discount contracts can simultaneously coordinate logistics service levels and retail prices [11]; Introducing logistics service cost sharing and revenue sharing contracts can achieve system coordination [12]; Joint decision-making can increase the profit margin of supply chain enterprises [13]; The decentralized decision-making supply chain cannot be coordinated through preservation cost sharing contracts, but can be coordinated through preservation cost sharing and revenue sharing contracts [14]. Decision makers on fresh agricultural products can jointly outsource logistics services to third-party logistics service providers and jointly bear the freight costs[15]. Due to information asymmetry, third-party logistics service providers face moral hazard issues [16]. Multiple contract alliances, such as "revenue sharing+dual cost sharing" contracts and "two-part tariffs+revenue sharing+dual cost sharing" coordination mechanisms [17], can also be considered. Consider the impact of 3PL preservation efforts on the freshness of fresh agricultural products, thereby affecting the overall decision-making of the fresh agricultural product supply chain [18]. Therefore, after third-party logistics service providers participate in the fresh agricultural product supply chain, how the logistics service level of third-party logistics service providers affects the decision-making behavior of the entire network of the fresh agricultural product supply chain and achieves a balanced state of the supply chain needs further research.

Professor Nagurney's research has brought the application of variational inequalities to solve the equilibrium problem of supply chain networks to the world, attracting the attention of domestic and foreign experts and scholars, and achieving many excellent results [19]. Qiang X [20] explores the impact of loss ratio and price elasticity on the equilibrium of fresh agricultural product supply chain network under dynamic networks. Zhou Linan [21] explored the impact of consumer preferences for organic products and other influencing factors on the production and sales decisions and profits of supply chain network members. PengY analyzed the sensitivity of the demand market to service quality, the relative importance of improving service quality by service providers, and the impact on the equilibrium state of the supply chain network based on a three-level PSSC network structure composed of service providers, platform operators, and demand markets.He also established a PSSC network equilibrium model in 2023, considering the dual risks faced by products and services[22-23]. Fargetta G[24] argue that a supply chain logistics network involves both forward and reverse logistics competition. Xiao Y X[25] believe that in a highly integrated supply chain system, the balance between after-sales service and product quality becomes an important consideration for establishing and maintaining sustainable supply chain partnerships. BesikD[26] developed an integrated multi-layer competitive agricultural product supply chain network model, in which agricultural product companies and processing companies compete to sell their differentiated products, fresh agricultural products, and minimally processed such fresh agricultural products, with guaranteed quality. Therefore, the network structure model can clearly represent the supply relationship between members of each layer of the supply chain network. However, there is very little literature on introducing third-party logistics into the fresh agricultural product network equilibrium model as the decision-making subject.

In summary, domestic and foreign scholars have conducted research on the decision-making optimization problem of traditional supply chain and fresh agricultural product supply chain network equilibrium, but there is little literature on constructing a fresh agricultural product supply chain network equilibrium model with third-party logistics participation to analyze the impact of 3PL service providers' logistics service level on the decision-making behavior of network members. This article constructs an equilibrium model for the supply chain network of fresh agricultural products, characterizes the impact of third-party logistics participation in decision-making on the equilibrium decision-making of the supply chain network of fresh agricultural products. Based on the actual business situation of 3PL service providers, it explores the changes in the equilibrium of the supply chain network of fresh agricultural products under the continuous changes in the logistics service level of 3PL service providers, and reconstructs the profit distribution mechanism of the supply chain network of fresh agricultural products, To provide useful references for reducing costs, achieving supply-demand balance, and making optimal decisions in the fresh agricultural product supply chain.

2. Model Description and Parameter Description

2.1. Model description

Consider 3PL service providers undertaking all logistics activities for fresh agricultural products from fresh agricultural product suppliers to the next level. Specifically, the fresh agricultural product suppliers entrust third-party logistics to undertake the logistics activities for their produced fresh agricultural products and pay relevant logistics service fees to 3PL service providers. In the fresh agricultural product supply chain network of 3PL service providers, the number of fresh agricultural product suppliers is m, the number of 3PL service providers is l, and the number of retailers is n. The structural relationship is shown in Figure 1. The goal of enterprises at all levels of the fresh agricultural product supply chain is to meet the demand of consumers in the demand market for fresh agricultural products, while maximizing their respective profits. The various merchants at each level have a non cooperative competitive relationship with each other. For convenience, we use i, o, and j to represent fresh agricultural product suppliers, 3PL service providers, and retailers, and then describe their optimal behavior and equilibrium conditions through variational inequalities to obtain an equilibrium model for the entire fresh agricultural product supply chain network. The ultimate goal is to achieve equilibrium among all three levels of participants.

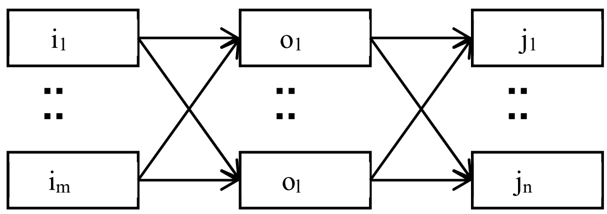

Figure 1. Three level supply chain including third-party logistics

The specific operation process of the three-level supply chain is as follows:

Step 1: Retailers determine the order quantity based on market demand information and sales price, and transmit the demand information to fresh agricultural product suppliers and 3PL service providers;

Step 2: Fresh agricultural product suppliers communicate with 3PL service providers based on ordering information to determine the shipment quantity and determine the transaction price;

Step 3: Fresh agricultural product suppliers pay service fees to 3PL service providers, who undertake storage and transportation tasks and provide logistics services such as preservation and handling;

Step 4: Fresh agricultural product suppliers and retailers trade quantity goods. Fresh agricultural product suppliers charge fees, and fresh agricultural product suppliers send out products. 3PL service providers transport the products to the retailers;

Step 5: Retailers sell products to the market to generate revenue.

In reality, the equilibrium of the supply chain network of fresh agricultural products is influenced by many practical factors. In order to facilitate the construction of the model and further research, the following assumptions are established:

Assuming that the cold chain transportation stage of the 1:3PL service provider is fully operational, product deterioration can be ignored, and deterioration only occurs in the inventory stage;

Assumption 2: The supply chain network does not allow out of stock, and the production capacity of fresh agricultural product suppliers can fully meet market demand;

Assumption 3: The supply chain network instantly replenishes goods without considering the lead time of the order;

Assumption 4: Retailers uniformly represent the next level trading entity of fresh agricultural product suppliers;

Assumption 5: Once the product deteriorates, no remedial measures are taken and it does not enter downstream circulation;

Assumption 6: The inventory of each participating decision-making entity in the initial and final cycle of the process is zero;

Assumption 7: The production function and transaction cost function designed in the model are both continuous differentiable convex functions.

2.2. Parameter Description

Table 1. Parameter Description

Parameter	Description
q_i	Production volume of fresh agricultural product suppliers
q_{ij}	Transaction volume between fresh agricultural product suppliers and retailers
q_{jk}	Retailer and external market transaction volume
P_{ij}	Transaction unit price between fresh agricultural product suppliers and retailers
P_{jk}	The transaction unit price that the external market is willing to bear
v_o	Service fees paid by fresh agricultural product suppliers to 3PL service providers
τ	3PL service provider logistics service level
l	Service level base
θ	Freshness of agricultural products
ϕ	Demand market preference for fresh agricultural products
ω	Total inventory cycle of 3PL service providers
t	Single order time
T	Expiry date of fresh agricultural products
$\lambda(t)$	Constructing loss factors based on freshness and supply loss ratio
$\delta(t)$	Effective proportion factor of fresh agricultural products
$F_i(q_i)$	Production cost function of fresh agricultural product suppliers
$C_{io}(q_i)$	The first transportation cost borne by 3PL service providers
$C_{oj}(q_{ij})$	The second transportation cost borne by 3PL service providers
$H_o(q_i)$	Inventory Cost Function of 3PL Service Providers
$G_o(q_i)$	The Deterioration Cost Function of 3PL Service Providers
$S_J(q_J)$	Retailer's transaction costs
r_{ij}	Supply batches from fresh agricultural product suppliers to retailers
π_i	Profit of fresh agricultural product suppliers
π_o	Profit of 3PL service providers
π	The overall profit of the fresh agricultural product supply chain

Considering the natural phenomenon that the freshness of agricultural products decreases over time and accelerates deterioration, we construct a freshness function by The $\theta = 1 - \frac{t^2}{T^2}$。Based on the freshness and supply loss ratio, a loss factor of the $\lambda(t)$ is constructed to describe the attenuation law of fresh agricultural product loss during the storage process. The effective proportion factor constructed through the loss factor is the $\delta(t)$.

Among them:

$$\lambda(t) = e^{\frac{\ln 2}{T}t} - 1 \tag{1}$$

And

$$\delta(t) = 1 - \lambda(t) = 2 - e^{\frac{\ln 2}{T}t}, \delta(t) \in [0,1] \tag{2}$$

That is to say, when a retailer requires a quantity of The q product, they actually order The $\frac{q}{2 - e^{\frac{\ln 2}{T}t}}$ from the manufacturer.

3. Construction of An Equilibrium Model for Agricultural Product Supply Chain Network

3.1. Optimization model and equilibrium conditions for fresh agricultural product suppliers

Fresh agricultural product suppliers outsource their logistics activities to third-party logistics, hand over the harvested agricultural products directly to 3PL service providers, and bear all outsourcing service fees in the form of unit agricultural products. Revenue is still generated through direct transactions with multiple retailers, as shown in Figure 2.

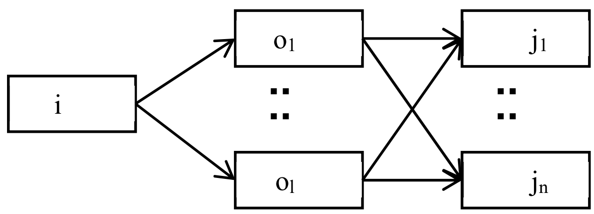

Figure 2. Network structure of fresh agricultural product suppliers

We assume the q_i is the production volume of fresh agricultural product suppliers, and the production batches of all fresh agricultural product suppliers form a column vector $Q_1 \in Rm$. The q_{ij} is the transaction volume between fresh agricultural product suppliers and retailers, and all transaction volumes form a column vector $Q_2 \in R_{mn}$. The P_{ij} represents the transaction price between fresh agricultural product suppliers and retailers, which is an endogenous variable. The r_{ij} is the batch of fresh agricultural products ordered by retailers from suppliers.The v_o is the unit logistics service fee for fresh agricultural products paid by suppliers to 3PL service providers.The $F_i(q_i)$ is the cultivation cost for fresh agricultural products produced by suppliers, and the $G_o(q_i)$ is the deterioration cost compensated by 3PL service providers to fresh agricultural products suppliers.

Every supplier of fresh agricultural products must pursue maximum profit. The profit of fresh agricultural product suppliers is the profit obtained from trading with each retailer, which is the price of agricultural products multiplied by the transaction quantity, minus production costs, logistics outsourcing service fees, and then adding compensation for deterioration. In the cycle ω If the supply batch of fresh agricultural product suppliers to retailers is the r_{ij}, the profit optimization function of fresh agricultural product suppliers is as follows:

The profit maximization model for fresh agricultural product suppliers is:

$$Max\pi_i = \sum_{j=1}^{n} P_{ij} q_{ij} r_{ij} + \sum_{i=1}^{m} G_o(q_i) - F_i(q_i) - \sum_{o=1}^{l} q_i v_0 \tag{3}$$

$$s.t. \begin{cases} \sum_{j=1}^{n} q_{ij} \le q_i \delta \left(\frac{\omega}{r_{ij}} \right) \\ q_i \ge 0, i = 1, 2, A \ , m \\ q_{ij} \ge 0, j = 1, 2, B \ , n \end{cases} \tag{4}$$

The first constraint in equation (4) represents that the transaction volume between fresh agricultural product suppliers and retailers does not exceed the production volume of fresh agricultural product suppliers, while the second and third constraints represent non negative decision variables.

Assuming that all cost functions of fresh agricultural product supplier i are continuously differentiable convex functions, and since all fresh agricultural product suppliers are non cooperative competitive relationships, under equilibrium state, according to the relationship between variational inequalities and optimization problems discussed earlier, the condition for all fresh agricultural product suppliers to simultaneously reach the optimal is equivalent to the solution of the following variational inequalities, that is, finding the optimal solution of (5):

$$\begin{aligned} &\sum_{i=1}^{m} \sum_{o=1}^{l} \left(\frac{\partial F_i(q_i^*)}{\partial q_i} + \frac{\partial q_i^* v_0}{\partial q_i} - \frac{\partial G_o\left(q_i^*\right)}{\partial q_i} - \gamma_i^* \right) \left(q_i - q_i^* \right) \\ &+ \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\gamma_i^* - P_{ij} r_{ij}^* \right) \left(q_{ij} - q_{ij}^* \right) \\ &+ \sum_{i=1}^{m} \left(q_i^* \delta \left(\frac{\omega}{r_{ij}} \right) - \sum_{j=1}^{n} q_{ij}^* \right) \left(\gamma_i - \gamma_i^* \right) \ge 0 \end{aligned} \tag{5}$$

In inequality (5),the γ_i^* is the Lagrange multiplier for fresh agricultural product suppliers with respect to constraint condition (4).From the first item of inequality (5), it can be seen that as long as the agricultural products produced by fresh agricultural product suppliers are positive, then the γ_i^* is equal to the unit production cost of fresh agricultural products produced by fresh agricultural product suppliers plus logistics service fees minus deterioration compensation. From the second item, it can be seen that as long as the transaction volume between fresh agricultural product suppliers and retailers is positive, the transaction price between fresh agricultural product suppliers and retailers is equal to the γ_i^*. From the third item, it can also be concluded that the γ_i^* is the sales price of fresh agricultural products sold by suppliers to retailers.

3.2. Optimization Model and Equilibrium Conditions for 3PL Service Providers

3PL service providers are at the core of the fresh agricultural product supply chain, responsible for the transportation and storage functions of fresh agricultural products. Gain revenue by charging logistics service fees to fresh agricultural product suppliers, and bear transportation costs, inventory costs, and deterioration costs. The transaction flowchart is shown in Figure 3:

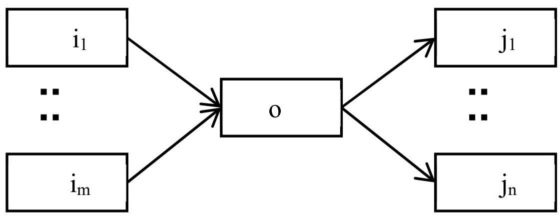

Figure 3. 3PL Service Provider Network Structure

We assume that v_o is the unit logistics service fee charged by 3PL service providers to fresh agricultural product suppliers. The q_i is the production volume of fresh agricultural product suppliers, as 3PL service providers are responsible for all logistics tasks from fresh agricultural product suppliers to the next level, The q_i is the inventory of 3PL service providers, forming a column vector $Q_1 \in Rm$. The q_{ij} is the transaction volume between fresh agricultural product suppliers and retailers, forming a column vector $Q_2 \in R_{mn}$. The C_{io} refers to the transportation cost between fresh agricultural product suppliers and 3PL service providers, which is determined by the production volume of fresh agricultural product suppliers, i.e. $C_{io}(q_i)$. The C_{oj} is the transportation cost between 3PL service providers and retailers, which is determined by the transaction volume between fresh agricultural product suppliers and retailers, i.e. $C_{oj}(q_{ij})$. The $H_o(q_i)$ is the inventory cost related to the production volume of fresh agricultural product suppliers. The $G_o(q_i)$ is the deterioration cost related to the production volume of fresh agricultural product suppliers, and all of the above costs are related to the logistics service level. The r_{ij} is the order batch from retailers to fresh agricultural product suppliers.

The operating principle of 3PL service providers is to pursue maximum profit. The profit of service providers is equal to the logistics service fee per unit of fresh agricultural products multiplied by the production volume of fresh agricultural product suppliers, minus transportation costs, inventory costs, and deterioration costs.

From this, it can be concluded that the profit maximization model for 3PL service providers is:

$$\begin{aligned} Max\pi_o &= \sum_{i=1}^{m}\sum_{j=1}^{n} q_i v_0 r_{ij} - \sum_{i=1}^{m} C_{io}\left(q_i\right) \\ &-\sum_{i=1}^{m}\sum_{j=1}^{n} C_{oj}\left(q_{ij}\right) - \sum_{i=1}^{m} H_o\left(q_i\right) - \sum_{i=1}^{m} G_o\left(q_i\right) \end{aligned} \tag{6}$$

$$s.t.\begin{cases} \sum_{j=1}^{n} q_{ij} r_{ij} \le \sum_{i=1}^{m} q_i \delta\left(\frac{\omega}{r_{ij}}\right) \\ q_i \ge 0, i = 1,2,\ldots,m \\ q_{ij} \ge 0, i = 1,2,\ldots,m, j = 1,2,\ldots n \end{cases} \tag{7}$$

The first constraint in equation (7) indicates that the 3PL service provider experiences a loss in supply during the inventory process, and the proportion of loss is related to the inventory time.The $\frac{\omega}{r_{ij}}$ is the total cycle time divided by the order batches within the cycle, which is the supply interval. At the same time, the 3PL service provider's effective quantity of agricultural products during the supply interval must be sufficient to meet the demand of all retailers in the next level. The second and third constraints indicate that the production volume of fresh agricultural product suppliers is not negative, and the transaction volume between fresh agricultural product suppliers and retailers is not negative.

According to the theoretical knowledge of variational inequalities, this expression can be transformed into the following variational inequalities for 3PL service providers:

$$\begin{aligned} &\sum_{i=1}^{m}\left(\frac{\partial C_{io}\left(q_i^*\right)}{\partial q_i} + \frac{\partial H_o\left(q_i^*\right)}{\partial q_i} + \frac{\partial G_o\left(q_i^*\right)}{\partial q_i} + \gamma_o^* - v_o r_{ij}\right)\left(q_i - q_i^*\right) \\ &+\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{o=1}^{l}\left(\frac{\partial C_{oj}\left(q_{ij}^*\right)}{\partial q_{ij}} - \gamma_o^*\right)\left(q_{ij} - q_{ij}^*\right) \\ &+\left(\sum_{i=1}^{m} q_i \delta\left(\frac{\omega}{r_{ij}}\right) - \sum_{j=1}^{n} q_{ij} r_{ij}\right)\left(\gamma_o - \gamma_o^*\right) \ge 0 \end{aligned} \tag{8}$$

In inequality (8), the γ_o is the Lagrange multiplier for the 3PL service provider with respect to the constraint condition (7). From the first term of inequality (8), it can be seen that if the quantity of agricultural products supplied by fresh agricultural product suppliers is positive, then the γ_o is equal to the logistics service cost of 3PL service providers minus the transportation cost, inventory cost, and deterioration cost per unit of agricultural products. From the second item, it can be seen that if the transaction volume between fresh agricultural product suppliers and retailers is positive, then the γ_o is exactly equal to the marginal transportation cost borne by the 3PL service provider from the service provider to the retailer. From the third item, it can be concluded that the γ_o is the actual transportation cost borne by the 3PL service provider from the service provider to the retailer.

3.3. Retailer Optimization Model and Equilibrium Conditions

In the supply chain of fresh agricultural products, transactions that occur through traditional retail channels depend on the relationship between the sum of various costs borne by retailers and the unit price of agricultural products that can be accepted by the external demand market. The transaction flowchart is shown in Figure 4:

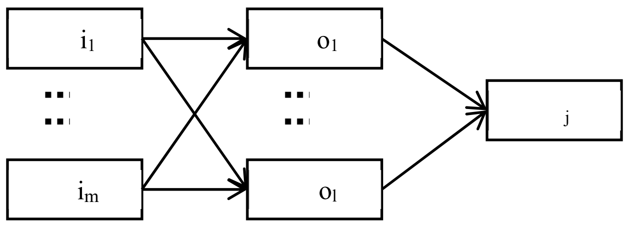

Figure 4. Retailer Network Structure Diagram

Within a fixed cycle, the unit exhibition cost, unit product storage cost, and deterioration cost borne by retailers are collectively referred to as transaction costs. Establish a decision-making model for retailers as follows:

The equilibrium relationship between the transaction costs borne by retailers and the transaction prices borne by external markets:

$$P_{ij} + S_j \begin{cases} = P_j; q_{ij} > 0 \\ \ge P_j; q_{ij} = 0 \end{cases} \tag{9}$$

The supply-demand balance between retailers and external markets:

The total demand from the external market is $d_j(P_j)$

And so

$$d_j(P_j)\begin{cases} = r_{ij}\sum_{i=1}^{m} q_{ij}\delta\left(\frac{\omega}{r_{ij}}\right); P_j > 0 \\ \le r_{ij}\sum_{i=1}^{m} q_{ij}\delta\left(\frac{\omega}{r_{ij}}\right); P_j = 0 \end{cases} \tag{10}$$

Joint formula (9) indicates that when the price of the product that the external market is willing to pay is less than the sum of the unit purchase price, unit exhibition price, inventory cost, and deterioration cost borne by the retailer, the external market will not purchase agricultural products, i.e. the transaction volume is zero. On the contrary, forming transactions and completing fresh agricultural product transactions in the supply and demand market; Joint equation (10) indicates that in an equilibrium state, the external market is willing to purchase products from retailers at a price greater than zero, which is equal to the total market demand. That is, when the quantity of products purchased by retailers in the external demand market is greater than the market demand, consumers will not purchase goods, that is, the sales price of agricultural products at this time is zero.

In the equilibrium state of the network, for each external demand market, both joint equations (9) and joint equations (10) must be satisfied simultaneously, then the optimal behavior of the retailer layer is equivalent to the following variational inequality, that is, finding the solution of

$$\sum_{j=1}^{n}\left[r_{ij}\sum_{i=1}^{m}q_{ij}^{*}\delta\left(\frac{\omega}{r_{ij}}\right)-d_j(P_j^{*})\right]\left(P_j-P_J^{*}\right)+ \sum_{i=1}^{m}\sum_{j=1}^{n}\left(P_{ij}+S_j\left(q_{ij}^{*}\right)-P_J^{*}\right)\left(q_{ij}-q_{ij}^{*}\right)\geq 0 \quad (11)$$

3.4. An Equilibrium Model for the Supply Chain Network of Fresh Agricultural Products

In an equilibrium state, the decision of all members in the cold chain network of agricultural products is the stable optimal solution in a common game state. According to the literature, when the cold chain network of agricultural products reaches an equilibrium state, fresh agricultural product suppliers, 3PL service providers, and retailers must simultaneously satisfy inequality (5), (8), and (11), that is, the sum of the three variational inequalities of inequality (5), inequality (8), and inequality (11). Therefore, the equilibrium condition of the agricultural product cold chain logistics network constructed in this section is equivalent to the solution of the following variational inequality (12), which is solved to x=(Q_1,Q_2， P_{ij} ， γ_i^{*} ， γ_o ， γ_j^{*})satisfy the

$$\begin{aligned}&\sum_{i=1}^{m}\sum_{o=1}^{l}\left(\frac{\partial F_i(q_i^{*})}{\partial q_i}+\frac{\partial q_i^{*}v_0}{\partial q_i}-\frac{\partial G_o\left(q_i^{*}\right)}{\partial q_i}-\gamma_i^{*}\right)\left(q_i-q_i^{*}\right)+\\&\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\gamma_i^{*}-P_{ij}r_{ij}^{*}\right)\left(q_{ij}-q_{ij}^{*}\right)+\sum_{i=1}^{m}\left(q_i^{*}\delta\left(\frac{\omega}{r_{ij}}\right)-\sum_{j=1}^{n}q_{ij}^{*}\right)\left(\gamma_i-\gamma_i^{*}\right)+\\&\sum_{i=1}^{m}\sum_{o=1}^{l}\left(\frac{\partial C_{io}\left(q_i^{*}\right)}{\partial q_i}+\frac{\partial H_o\left(q_i^{*}\right)}{\partial q_i}+\frac{\partial G_o\left(q_i^{*}\right)}{\partial q_i}+\gamma_o^{*}-v_0r_{ij}\right)\left(q_i-q_i^{*}\right)\\&+\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{\partial C_{oj}\left(q_{ij}^{*}\right)}{\partial q_{ij}}-\gamma_o^{*}\right)\left(q_{ij}-q_{ij}^{*}\right)+\\&\left(\sum_{i=1}^{m}q_i\delta\left(\frac{\omega}{r_{ij}}\right)-\sum_{j=1}^{n}q_{ij}r_{ij}\right)\left(\gamma_o-\gamma_o^{*}\right)+\sum_{j=1}^{n}\left[r_{ij}\sum_{i=1}^{m}q_{ij}^{*}\delta\left(\frac{\omega}{r_{ij}}\right)-d_j(P_j^{*})\right]\left(P_j-P_J^{*}\right)\\&+\sum_{i=1}^{m}\sum_{j=1}^{n}\left(P_{ij}+S_j\left(q_{ij}^{*}\right)-P_J^{*}\right)\left(q_{ij}-q_{ij}^{*}\right)\geq 0\end{aligned} \quad (12)$$

4. Example Analysis

The manuscript should include a conclusion. In this section, summarize what was described in your paper. Future directions may also be included in this section. Authors are strongly encouraged not to reference multiple figures or tables in the conclusion; these should be referenced in the body of the paper.

In order to simplify the calculation, this article will take the fresh agricultural product supply chain network composed of two fresh agricultural product suppliers, two 3PL service providers, and two retailers as an example to conduct an equilibrium analysis of the entire network. The specific network structure is shown in Figure 5.

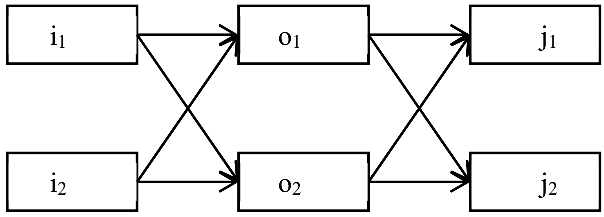

Figure 5. Example diagram of fresh agricultural product supply chain network structure

The circulation of fresh agricultural products among various decision-making entities in the supply chain can be well reflected based on inventory status. The inventory status of decision-makers at all levels is shown in Figure 6.

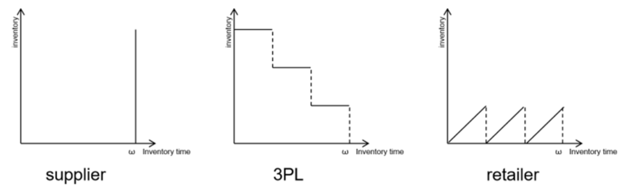

Figure 6. Inventory status of decision-makers at all levels over two cycles

The specific forms of setting cost functions and parameters for participants at all levels are as follows：

Cost function for cultivating fresh agricultural product suppliers:

$$F_1\left(q_1\right)=2.5(q_1)^2+q_1q_2+2q_1$$

$$F_2\left(q_2\right)=2.5(q_2)^2+q_1q_2+2q_2$$

Logistics service fees:

$$v_1=0.25q_1l\tau^2p_{ij}$$

$$v_2=0.25q_2l\tau^2p_{ij}$$

The transportation cost function between fresh agricultural product suppliers and 3PL service providers:

$$C_{11}\left(q_{11}\right)=l\tau^2\left(q_{11}{}^2+3.5q_{11}\right)$$

$$C_{21}\left(q_{21}\right)=l\tau^2\left(q_{21}{}^2+3.5q_{21}\right)$$

$$C_{12}\left(q_{12}\right)=l\tau^2\left(q_{12}{}^2+3.5q_{12}\right)$$

$$C_{22}\left(q_{22}\right)=l\tau^2\left(q_{22}{}^2+3.5q_{22}\right)$$

Inventory cost function for 3PL service providers:

$$H_1(q_1)=0.5r_{ij}(\delta(t)q_{11}+\delta(t)q_{21})^2,\delta(t)=2-e^{\frac{\ln 2}{T}\frac{\omega}{r_{ij}}}$$

$$H_2(q_2)=0.5r_{ij}(\delta(t)q_{12}+\delta(t)q_{22})^2,\delta(t)=2-e^{\frac{\ln 2}{T}\frac{\omega}{r_{ij}}}$$

The Deterioration Cost Function of 3PL Service Providers:

$$G_1(q_1)=0.5r_{ij}(\lambda(t)q_{11}+\lambda(t)q_{21})^2,\ \ \lambda(t)=e^{\frac{\ln 2}{T}\frac{\omega}{r_{ij}}}-1$$

$$G_2(q_2)=0.5r_{ij}(\lambda(t)q_{12}+\lambda(t)q_{22})^2,\ \ \lambda(t)=e^{\frac{\ln 2}{T}\frac{\omega}{r_{ij}}}-1$$

The transportation cost function between 3PL service providers and retailers:

$$C_{11}\left(q_{11}\right)=l\tau^2\left(0.5q_{11}{}^2+3.5q_{11}\right)$$

$$C_{21}\left(q_{21}\right)=l\tau^2\left(0.5q_{21}{}^2+3.5q_{21}\right)$$

$$C_{12}\left(q_{12}\right)=l\tau^2\left(0.5q_{12}{}^2+3.5q_{12}\right)$$

$$C_{22}\left(q_{22}\right)=l\tau^2\left(0.5q_{22}{}^2+3.5q_{22}\right)$$

Retailer's transaction costs: $S_j\left(q_j\right)=q_j+5$

Demand market preferences: $\phi_1=2+60m$, $\phi_2=2+60m$

External market demand function for agricultural products:

$$d_1(p_3)=400+20\phi_1-p_{31}-2p_{32}$$

$$d_2(p_3)=400+20\phi_2-2p_{31}-p_{32}$$

The inequality (12) was solved using a modified projection algorithm and analyzed using MATLAB simulation software. The step size in the algorithm was set to 0.01, and the convergence standard was set to 10-8. For this example, the total inventory cycle is 30 days; Rij=3, the logistics service level coefficient of third-party logistics service providers l =4, and the equilibrium solution of the fresh agricultural product supply chain network obtained through iteration is shown in Table 2.

Table 2. Equilibrium Solution of Fresh Agricultural Product Supply Chain Network

Service level coefficient	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Number of iterations	1167	1178	1188	1199	1211	1223	1239	1260	1285
q_i	15.7699	19.1192	21.3888	22.4633	22.5074	21.8245	20.7185	19.4236	18.0930
q_{ij}	12.4507	15.9387	18.6647	20.3614	21.0449	20.9169	20.2338	19.2217	18.0460
q_{jk}	12.4497	15.9386	18.6637	20.3595	21.0421	20.9142	20.2316	19.2199	18.0447
P_{ij}	145.2207	176.7658	208.9102	241.8633	275.6123	309.9986	344.8208	379.9015	415.1108
P_{jk}	156.4417	189.7308	223.2379	257.0390	291.1297	325.4520	359.9327	394.5075	429.1290

At the same time, based on the inventory status of decision-makers at all levels, the average of initial inventory and final effective inventory is treated as the average inventory. Fresh agricultural product suppliers, 3PL service providers, and retailers are calculated to balance other decision variables when the cycle changes with logistics service levels. The specific equilibrium values are shown in Table 3.

Table 3. Equilibrium Results of Other Decision Variables

Service level coefficient	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$F_i(q_i)$	901.95	1317.64	1643.96	1811.03	1818.06	1710.74	1543.83	1359.31	1181.93
$q_i * v_o$	22.90	135.18	402.15	869.29	1550.83	2435.61	3500.64	4722.59	6083.58
$C_{io}(q_i)$	3.59	19.98	54.65	105.89	166.03	226.47	281.40	328.47	367.75
$C_{oj}(q_{ij})$	1.65	9.54	27.44	55.97	92.18	131.46	169.71	204.34	234.21
$H_o(q_i)$	9.30	60.97	188.12	398.00	664.33	945.04	1203.66	1418.77	1582.69
$G_o(q_i)$	16.53	15.17	11.13	6.63	3.21	1.24	0.35	0.06	0.01
$S_J(q_J)$	11.23	12.97	14.33	15.18	15.52	15.46	15.12	14.61	14.02
π_i	1799.28	2759.54	3728.53	4501.96	4869.10	4678.21	3865.84	2440.97	451.12
π_o	-26.81	0.01	77.46	281.85	733.69	1546.93	2788.83	4476.25	6593.94
π	1772.47	2759.54	3805.99	4783.81	5602.78	6225.15	6654.68	6917.22	7045.07

As shown in Figure 6, with the τ The increase in The P_{ij} and The P_j shows a stable and significant increase, indicating that the logistics service costs borne by fresh agricultural product suppliers actually have a price transmission mechanism, transferring some of the logistics costs to transactions with retailers to alleviate the burden of unilateral logistics service costs borne by fresh agricultural product suppliers. At the same time, it also indicates that the level of logistics service has a significant impact on transaction prices, Further reflecting the significant impact of changes in logistics service levels on the quality of fresh agricultural products.

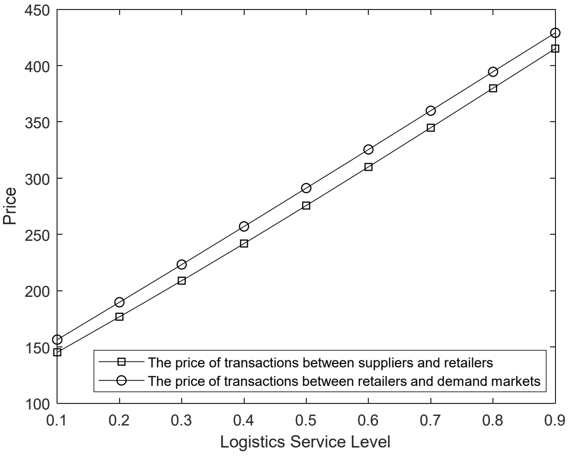

Figure 6. Price Trends of Various Transactions under Different Logistics Service Levels

As shown in Figure 7, when the τ When less than or equal to 0.5, with the τ The increase in the q_i, the q_{ij}, and the q_j indicates that improving the logistics service level of 3PL service providers can effectively stimulate consumption in the demand market, thereby increasing the supply volume of fresh agricultural product suppliers and enhancing the operational vitality of the fresh agricultural product supply chain. When The τ When greater than 0.5, with When greater τ With the increase of,the q_i, the q_{ij} and the q_j began to show a slight decrease, and the difference between output the q_i and the q_{ij} and the q_j became smaller. This indicates that when the logistics service level rises to a certain extent, it is affected by other factors (such as cold chain facilities and equipment, cold chain technology, and the characteristics of fresh agricultural products themselves). The impact of the improvement of logistics service level on the quality of fresh agricultural products gradually decreases, but the transaction price is still stable and increases due to price transmission, This leads to a decrease in equilibrium production and trading volume.

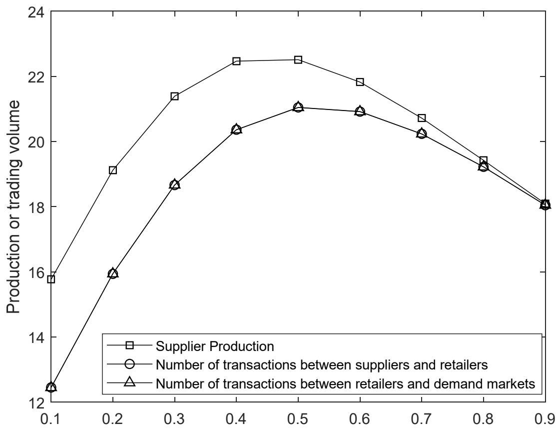

Figure 7. Trend of Fresh Agricultural Product Supplier Production and Various Transaction Volumes under Different Logistics Service Levels

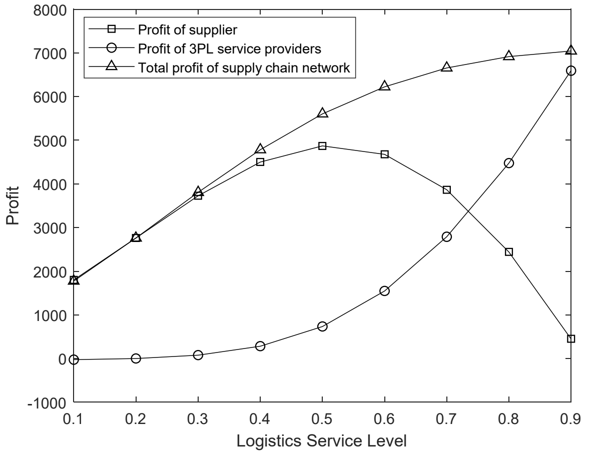

Figure 8. Profit Trends under Different Logistics Service Levels

As shown in Figure 8, the π_i varies with the τ The increase of appears to increase first, when the τ It reaches its peak at 0.5 and then gradually decreases. When the logistics service level is at a lower level, it has a significant impact on the quality improvement of fresh agricultural products. The transaction volume and prices of fresh agricultural product suppliers and retailers have increased. Although logistics service fees have increased, their value-added and revenue are relatively small, resulting in an upward trend in the profits of fresh agricultural product suppliers. However, as 3PL service providers and logistics service providers gradually increase their logistics service levels, their impact on improving the quality of fresh agricultural products gradually decreases when they are at a higher level. However, the input costs of logistics service levels continue to increase, leading to a continuous increase in logistics service fees, which are transmitted to the transaction prices between fresh agricultural product suppliers and retailers. As the transaction volume decreases, logistics service fees increase, The profits of fresh agricultural product suppliers are showing a downward trend. When τ When it is less than 0.2, the π_o is less than 0. When the logistics service level of 3PL service providers is too low, they can charge very little logistics service fees, and also pay compensation for the deterioration of fresh agricultural products caused by insufficient preservation efforts, making 3PL service providers unable to obtain profits. When τ When it is greater than or equal to 0.2, the π_o is greater than 0 and follows the τ The increase gradually increases. The higher the level of logistics service, the greater the profit obtained by 3PL service providers. the π with the τ The rapid growth followed by slow growth indicates that the improvement of logistics service level can improve the quality of fresh agricultural products, thereby achieving an increase in the overall profit of the fresh agricultural product supply chain. This is because the impact of logistics level on the quality of fresh agricultural products becomes smaller when it is at a higher level, resulting in a decrease in the overall profit growth rate of the fresh agricultural product supply chain.

5. Conclusion

Introducing third-party logistics service providers as separate decision-making entities to participate in fresh agricultural product supply chain decision-making, considering the loss characteristics of fresh agricultural products, demand preferences in the demand market, and the logistics service level of 3PL service providers, constructing a fresh agricultural product supply chain network model that includes fresh agricultural product suppliers, 3PL service providers, and retailers. The research results are as follows: (1) An appropriate increase in the logistics service level of 3PL service providers can improve the quality of fresh agricultural products and reduce losses, thereby increasing demand market preferences and the operational vitality of the fresh agricultural product supply chain. (2) Improving the logistics service level of 3PL service providers can increase the overall profit of the fresh agricultural product supply chain, while also enhancing the gaming position of 3PL service providers in the fresh agricultural product supply chain. (3) Improving the logistics service level of 3PL service providers will lead to a rapid and then slow increase in the overall profit of the fresh agricultural product supply chain, indicating that the improvement effect of logistics service level on the quality of fresh agricultural products gradually weakens after reaching a certain level.

Based on the above research results and practical situations, the following inspirations can be drawn: (1) Fresh agricultural product suppliers and 3PL service providers should maintain a high degree of information sharing to avoid the mismatch between the logistics services and cold chain levels provided by 3PL and the logistics service fees charged, which will cause transaction prices to rise after transmission, but the quality of fresh agricultural products will not be correspondingly improved, which will seriously reduce transaction volume, Affects the late decision-making of fresh agricultural product suppliers, leading to a vicious cycle and collapse of the entire fresh agricultural product supply chain. (2) By investing in the research and development of cold chain logistics technology, we can improve the efficiency of cold chain facilities and equipment, as well as the level of cold chain technology, to achieve "cost reduction and efficiency increase". This avoids the insignificant improvement in the quality of fresh agricultural products as the service level increases when the logistics service level is high, and can also weaken the price transmission and continuously enhance the vitality of the fresh agricultural product supply chain operation, Matching fresh agricultural products with different consumption characteristics with appropriate logistics service levels can also achieve the same effect.

This article mainly explores the impact of logistics service level on the equilibrium of the fresh agricultural product supply chain network, without considering the cooperation strategies between 3PL service providers and other decision-making entities on the supply chain network. In future research, the impact of this factor on the equilibrium solution will continue to be considered.

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