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An Optimal Decision of Fresh Products Cold Chain Considering Freshness and Carbon Emission Reduction

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Abstract: Fresh products cold chain has the characteristics of high energy consumption and high carbon emission. Based on the policy background of carbon cap-and-trade, cold chain decision-makers need to comprehensively consider the relationship between economic and ecological benefits. Therefore, this paper constructs a fresh products cold chain optimal decision game model considering retailers' fresh-keeping efforts and suppliers' carbon emission reduction efforts, and compares the optimal decision-making of cold chain under different carbon constraints. Finally, the impact of consumer freshness preference and consumer low-carbon preference on retailers' fresh-keeping efforts, suppliers' carbon emission reduction efforts and cold chain system profits are numerically analyzed. The results show that the profits of the fresh products cold chain system under the carbon cap-and-trade policy are higher than those without carbon constraints; Raising the carbon trading price can effectively improve the fresh-keeping level, carbon emission reduction level and system profit of the cold chain of fresh products; The improvement of consumers' freshness preference and low-carbon preference can increase the profits of the cold chain system, reduce carbon emissions and promote the sustainable development of the cold chain to a certain extent.

Keywords: Freshness-keeping effort; Carbon emission reduction; Fresh products; Cold chain optimal decision

1. Introduction

With the continuous improvement of material living standards, people have higher and higher requirements for the quality of fresh products. The freshness of fresh products is closely related to demand. However, due to the continuous perishable vulnerability of fresh products, this characteristic is not only reflected in the physical loss caused by loading, unloading and handling in the circulation process, but also reflected in the value loss caused by natural physical deterioration in the retail channel, which directly affects the sales volume and income [1]. In addition, in the fresh-keeping, transportation and distribution process of fresh food cold chain, high energy consumption and high carbon emissions will occur [2]. Crucially, more and more road transportation refrigeration technologies occupy a huge position in the world. 40% of food needs refrigeration, and 15% of the world's fossil fuel energy is used for food transportation refrigeration. Due to the increase of the world's population, the energy consumption of the cold chain is expected to rise significantly [3]. Under the guidance of the low-carbon policy in the future, the carbon emissions of the cold chain will gradually tend to be controlled. Therefore, in the current low-carbon economic environment, the decision-makers of the cold chain of fresh products should not only pay attention to economic interests, but also pay attention to invest in emission reduction, cooperative emission reduction and other behaviors to improve ecological benefits [4].Such behavior characteristics also have an indirect impact on the demand for fresh products, thus changing the overall profits of the cold chain of fresh products and the profit distribution of each subject of the cold chain.

Based on the background of carbon cap-and-trade policy, this paper constructs a game decision model for fresh products cold chain under different carbon constraint scenarios by considering both fresh products freshness level and cold chain system carbon reduction level. Through the research on the optimal decision-making of the fresh products cold chain under the carbon cap-and-trade policy, this paper also provides some reference and suggestions for the decision-makers of the cold chain enterprises in the carbon emission reduction decision-making, helps the fresh products cold chain enterprises to develop better and promotes the sustainable development of the fresh products cold chain system.

The rest of this paper is organized as follows: Section 2 sorts out the contributions and shortcomings of related research fields. The problem description and underlying assumptions will be introduced in Section 3. Section 4 will construct and solve a game decision model for fresh products cold chain under different carbon constraint scenarios. Numerical analysis and simulation will be presented in Section 5 and conclusions will be drawn in the last section.

2. Literature Review

Fresh products have the characteristics of perishable and short life cycle, so freshness has always been an important research object in the cold chain. Wang et al. introduced time and fresh-keeping efforts into the cold chain system to analyze the impact on the consumption of fresh products. Considering the impact of freshness and price on demand, they analyzed the most common pricing and inventory strategies of the cold chain system [5]. Li et al. analyzed and studied the joint optimization scheme of cold chain logistics based on the constraints of freshness and delivery time [6]. Cao et al. studied the efforts of suppliers to keep fresh and designed and constructed contract models such as pricing contract, wholesale price coordination contract and hybrid coordination contract. The research shows that the three contracts can effectively achieve supply chain coordination within a certain range and improve the profits of all members [7]. Sun et al. considered altruistic preferences, freshness and transportation loss characteristics, established a decision-making model for fresh agricultural products supply chain, and studied the optimal decision-making when supply chain subjects have different altruistic preferences [8]. Feng et al. constructed a two-level fresh products supply chain decision model consisting of risk-neutral suppliers and risk-averse retailers to achieve supply chain coordination, considering that the demand for fresh produce is influenced by product freshness and price [9]. Zheng et al. studied the optimal pricing strategy of the supply chain under the centralized decision-making and decentralized decision-making mode on the premise of considering the fresh-keeping effect of fresh products [10]. Li et al. considered the factor of freshness in the demand function and established a pricing inventory joint decision-making model to analyze the optimal decision-making of retailers under the two demand behaviors of loss neutrality and loss aversion [11]. Song et al. considered the freshness in the market demand, and studied the influence of market preference on cold chain decision-making and profit by establishing game models under different decision-making situations based on two contract types of cost sharing and merger rebate [12]. Wu et al. proposed a virtual cold chain (VCC) method to predict the temperature history and quality loss of packaged fresh fruits [13]. Liu et al. studied a dynamic control model of freshness level composed of online retailers and offline manufacturers to improve the freshness level at the time of delivery [14]. Kartoglu et al. proposed that in the process of cold chain transportation, temperature is very important for the freshness and quality of products [15].

With the development of low-carbon economy, the decision-making of low-carbon production of fresh products cold chain has increasingly become a research hotspot. Wu et al. realized the environmental trade-off of fresh fruit cold chain by combining virtual cold chain with life cycle assessment [16]. Dong et al. evaluated the life cycle greenhouse gas (GHG) emissions of perishable food transported in the cold chain in China [17]. Ma et al. studied the fresh-keeping, carbon emission reduction, pricing and other decisions of the cold chain system in the supplier TPLSP retailer three-level cold chain system when TPLSP undertakes the fresh-keeping and low-carbon responsibilities of fresh products at the same time [18]. Li et al. Studied the carbon emission reduction and pricing strategy of the cold chain when retailers have fair concern behavior [19]. Ye and Zhao used principal component analysis (PCA) to analyze the factors affecting the collaborative development level of new retail and cold chain distribution of agricultural products under low-carbon conditions. This research is conducive to improving the downstream supply chain management ability of new agricultural retail enterprises, improving the efficiency and business value of cold chain distribution [20]. Liu et al. applied the evolutionary game model to the two-level green supply chain system and found that the government regulation can effectively affect the "free riding" behavior of enterprises and promote the collaborative emission reduction of green supply chain enterprises [21]. Babagolzadeh et al. based on the iterative local search (ILS) algorithm and the mathematical algorithm of mixed integer programming, discussed the impact of carbon emissions in the cold chain storage and transportation of fresh products under the circumstances of carbon tax regulation and uncertain demand [22]. Alkaabneh et al. considered the impact of carbon tax, land conservation incentives and new emission reduction technologies on the carbon emissions of fresh fruit cold chain [23]. Hasan et al. optimized the cold chain inventory level and technology investment under the carbon tax, carbon cap-and-trade policy [24]. Roy et al. evaluated the synergy between cold chain preservation technology and carbon cap-and-trade policy [25]. Jean et al. developed an innovative model for calculating the CO_2 emissions of each stage of the cold chain in all countries in the world, and compared the CO_2 emissions of the current global cold chain with those of the improved cold chain [26]. Under the carbon cap-and-trade policy, Zhang et al. constructed the location optimization model of urban cold chain logistics low-carbon emission competitive distribution center. The research shows that the change of carbon emission quota policy and carbon trading price can affect the scale, total carbon emission and total social cost of the new cold chain distribution center [27].

As'ad et al. used Lagrangian Relaxation method to compare the operating costs and carbon footprint performance of fresh products cold chain under carbon tax and carbon quota policies [28]. Most of the above documents only consider the impact of single or partial factors such as price, freshness or carbon emission reduction level on the demand for fresh products, but few studies have analyzed the changes in the demand for fresh products under the combined influence of multiple factors.

It can be seen from the existing literature that the issue of cold chain freshness and low-carbon emission reduction has become a hot topic in cold chain research. However, most of the above-mentioned literatures only consider the impact of single or partial factors such as price, freshness or carbon emission reduction level on the demand for fresh products, and few studies analyze the changes in the demand for fresh products under the combined influence of multiple factors. Based on this, aiming at the two-level fresh products cold chain system of suppliers and retailers, this paper studies the optimal decision of the system under the carbon cap-and-trade policy. Compared with the existing research, the innovations of this paper are as follows: (1) Considering the freshness level of suppliers and the carbon emission reduction level of retailers, we explore the comprehensive impact of freshness level and carbon emission reduction level on the demand for fresh products. (2) We compared the decision-making and benefits of decentralized and centralized cold chain systems under different carbon constraints, providing more theoretical basis for low-carbon decision-making. (3) The impact of consumer freshness preference and low carbon preference on the economic and environmental benefits of the cold chain system is explored to promote the sustainable development of the fresh products cold chain.

3. Problem Description and Underlying Assumptions

This paper considers a secondary fresh product cold chain system composed of one supplier and one retailer. In which the supplier of fresh product is dominant in the cold chain, which determines the wholesale price of fresh product based on supply and demand, and the retailer determines the fresh product retail unit price based on the supplier's decision and market demand. In addition, the freshness level and level of carbon reduction in the cold chain system of fresh products can also affect fluctuations in retail prices and demand.

Hypothesis 1: assuming that each subject of the cold chain markets only one fresh product and that the two parties are information symmetric during the course of carrying out a pricing game, that is, that both parties have full access to the strategies that the other takes during the pricing process.

For convenience of research, uniform pricing is assumed to operate both online and offline. At the same time when consumers purchase fresh products, freshness is a key factor affecting their purchase decision, so freshness factor is considered in the demand function.

Hypothesis 2: assuming that the retailer carries both online and offline channels, the freshness when fresh products are transported from the supplier to the retailer is θ. When consumers purchase fresh products from an online channel, a folding loss is present along the way and the degree of the folding loss is θ_0. The degree of folding loss can be reduced by the preservation input to the fresh product, which reaches the retailer's freshness, which can be expressed by the function: $\theta(e)=\theta(1-\theta_0+e)$, where, e is the preservation effort, while carbon abatement has an impact on demand, and the sensitive coefficient of demand to change in the level of carbon abatement (consumer low-carbon preference) is u [7]. According to the above assumptions, the linear expressions of the online demand function and the offline demand function can be expressed as:

$$D_1=\beta d-p+\gamma\theta(e)+uv \tag{1}$$

$$D_2=(1-\beta)d-p+\gamma\theta+uv \tag{2}$$

$$Q=D_1+D_2 \tag{3}$$

Where: d represents the potential market demand and is infinitesimal; β represents the market proportion of the online channel; and correspondingly, $1-\beta$ represents the market proportion of the offline channel that satisfies $0<\beta<1$; γ represents the sensitive coefficient of demand to freshness variation (consumer freshness preference); Q is the aggregate demand.

Hypothesis 3: the cost incurred by the product during transportation is included in the base cost, which assumes that the retailer incurs the preservation cost $c_e=\frac{1}{2}ke^2$, Where, k represents the coefficient of the effect of preservation effort on the cost of preservation, and e represents the preservation effort. Assuming that the supplier is responsible for the cost of carbon reduction $c_v=\frac{1}{2}\delta v^2$, where, δ represents the impact coefficient of the supplier's carbon reduction efforts on the cost of carbon reduction, and v represents the carbon reduction [18].

4. Model Construction and Solution

4.1. Decision model of fresh produce cold chain without carbon constraint under dispersal decision. In the carbon free constrained environment under the decentralized decision, both the raw food supplier and the raw food retailer are fully rational. The retailer used their own profit maximization as their principle and determined the retail price p and the level of preservation effort e based on the market situation. The supplier based on the retailer's response determines the product's level of carbon reduction v and wholesale price ω to maximize its profit.

In the decentralized decision model, the profit function of suppliers and retailers is expressed as:

$$\pi_1 = (\omega - c)Q - c_v = (\omega - c)[d - 2p + \gamma\theta + \gamma\theta(1 - \theta_0 + e) + 2uv] - \frac{1}{2}\delta v^2 \tag{4}$$

$$\pi_2 = (p - \omega)Q - c_e = (p - \omega)[d - 2p + \gamma\theta + \gamma\theta(1 - \theta_0 + e) + 2uv] - \frac{1}{2}ke^2 \tag{5}$$

Theorem 1: when $4k - \gamma^2\theta^2 > 0$, the profit function of both suppliers and retailers has an optimal solution.

Proof: based on the backward induction, the solution of the Stackelberg equilibrium is solved. Firstly, solve the first derivative of π_2 with respect to p and e as follows:

$$\frac{\partial \pi_2}{\partial p} = d - 4p + 2\omega + \gamma\theta + 2uv + \gamma\theta\left(e - \theta_0 + 1\right) \tag{6}$$

$$\frac{\partial \pi_2}{\partial e} = \gamma\theta\left(p - \omega\right) - ek \tag{7}$$

Accordingly, the Hessian matrix of π_2 is: $H_2 = \begin{bmatrix} -4 & \gamma\theta \\ \gamma\theta & -k \end{bmatrix}$. Let M_k be the k-th order major sub-formula of the Hessian matrix, then: $M_1 = -4$, $M_2 = 4k - \gamma^2\theta^2$. According to the negative definite judgment theorem of Hessian matrix, the negative definite condition of this Hessian matrix is $4k - \gamma^2\theta^2 > 0$. Let $\frac{\partial \pi_2}{\partial p} = 0$ and $\frac{\partial \pi_2}{\partial e} = 0$ to obtain the retailer's optimal response function:

$$p^* = \frac{dk + 2\omega k + 2\gamma\theta k + 2uvk - \gamma\theta_0\theta k - \gamma^2\omega\theta^2}{4k\text{-}\gamma^2\theta^2} \tag{8}$$

$$e^{*}=\frac{\gamma\theta\left(d-2\omega+2\gamma\theta+2uv-\gamma\theta_{0}\theta\right)}{4k-\gamma^{2}\theta^{2}} \tag{9}$$

Bring p^{*} and e^{*} into equation (4), and the supplier profit function is:

$$\begin{aligned}\pi_{1}=&\left(-\frac{4\delta k-\delta\gamma^{2}\theta^{2}}{2\left(4k-\gamma^{2}\theta^{2}\right)}\right)v^{2}+\left(-\frac{8cku-8k\omega u}{2\left(4k-\gamma^{2}\theta^{2}\right)}\right)v\\&-\frac{8k\omega^{2}+4cdk-8ck\omega-4dk\omega+8c\gamma k\theta}{2\left(4k-\gamma^{2}\theta^{2}\right)}\\&+\frac{+8\gamma k\omega\theta+4c\gamma k\theta_{0}\theta-4\gamma k\omega\theta_{0}\theta}{2\left(4k-\gamma^{2}\theta^{2}\right)}\end{aligned} \tag{10}$$

The Hessian matrix of π_1 is: $H_{1}=\begin{bmatrix}\frac{8k}{\gamma^{2}\theta^{2}-4k} & \frac{4ku}{4k-\gamma^{2}\theta^{2}}\\ \frac{4ku}{4k-\gamma^{2}\theta^{2}} & -\delta\end{bmatrix}$. Let M_k be the k-th order major sub-formula of the Hessian matrix, and there are: $M_{1}=\frac{8k}{\gamma^{2}\theta^{2}-4k}$, $M_{2}=-\frac{8k\left(\delta\gamma^{2}\theta^{2}+2ku^{2}-4\delta k\right)}{\left(4k-\gamma^{2}\theta^{2}\right)^{2}}$. According to the negative definite decision theorem of Hesse matrix, when $\frac{8k}{\gamma^{2}\theta^{2}-4k}<0$ and $-\frac{8k\left(\delta\gamma^{2}\theta^{2}+2ku^{2}-4\delta k\right)}{\left(4k-\gamma^{2}\theta^{2}\right)^{2}}>0$ the Hessian matrix is negative definite. Therefore, π_1 is a joint concave function of ω and v, which can be obtained as follows:

$$\omega^{*}=\frac{(8ck)u^{2}+2\delta\gamma^{3}\theta^{3}-8c\delta k-4d\delta k-8\delta\gamma k\theta+2c\delta\gamma^{2}\theta^{2}+d\delta\gamma^{2}\theta^{2}-\delta\gamma^{3}\theta_{0}\theta^{3}+4\delta\gamma k\theta_{0}\theta}{(8k)u^{2}+4\delta\gamma^{2}\theta^{2}-16\delta k} \tag{11}$$

$$v^{*}=\frac{ku\left(2c-d-2\gamma\theta+\gamma\theta_{0}\theta\right)}{\delta\gamma^{2}\theta^{2}+2ku^{2}-4\delta k} \tag{12}$$

By substituting ω^{*}, v^{*} into the optimal response functions p^{*} and e^{*}, we can get:

$$\begin{aligned}p^{*}=&\frac{8cku^{2}+2\delta\gamma^{3}\theta^{3}-4c\delta k-6d\delta k-12\delta\gamma k\theta}{8ku^{2}+4\delta\gamma^{2}\theta^{2}-16\delta k}\\&+\frac{2c\delta\gamma^{2}\theta^{2}+d\delta\gamma^{2}\theta^{2}-\delta\gamma^{3}\theta_{0}\theta^{3}+6\delta\gamma k\theta_{0}\theta}{8ku^{2}+4\delta\gamma^{2}\theta^{2}-16\delta k}\end{aligned} \tag{13}$$

$$e^{*}=\frac{\delta\gamma\theta\left(2c-d-2\gamma\theta+\gamma\theta_{0}\theta\right)}{2\delta\gamma^{2}\theta^{2}+4ku^{2}-8\delta k} \tag{14}$$

Substituting equation (11), (12), (13), (14) into equation (4), (5) respectively, the optimal profit and optimal demand of suppliers and retailers under centralized decision-making can be obtained:

$$Q_{1}=\frac{\delta k\left(2c-d-2\gamma\theta+\gamma\theta_{0}\theta\right)}{\delta\gamma^{2}\theta^{2}+2ku^{2}-4\delta k} \tag{15}$$

$$\pi_{1}=\frac{\delta k\left(2c-d-2\gamma\theta+\gamma\theta_{0}\theta\right)^{2}}{4\delta\gamma^{2}\theta^{2}-8ku^{2}+16\delta k} \tag{16}$$

$$\pi_{2}=\frac{\delta^{2}k\left(4k-\gamma^{2}\theta^{2}\right)\left(2c-d-2\gamma\theta+\gamma\theta_{0}\theta\right)^{2}}{8\left(\delta\gamma^{2}\theta^{2}+2ku^{2}-4\delta k\right)^{2}} \tag{17}$$

4.2. Fresh products cold chain decision model with carbon constraint under decentralized decision. In the environment with carbon constraints under decentralized decision-making, based on the carbon cap-and-trade policy, the government stipulates that the carbon emission quota is M , the carbon emission per unit product is f , and the carbon quota can be freely traded between enterprises, and the unit price is z .

In the cold chain pricing model of fresh products with carbon constraints under decentralized decision-making, the profit function of suppliers and retailers is expressed as:

$$\begin{aligned}\pi_{3}&=(\omega-c)Q+z[M-(f-v)Q]-c_{v}\\&=(\omega-c)[d-2p+2uv+2\gamma\theta-\gamma\theta\theta_{0}+e\gamma\theta)]\\&\quad+z(M-(f-v)(d-2p+2\gamma\theta+2uv+e\gamma\theta-\gamma\theta\theta_{0}))-\frac{1}{2}\delta v^{2}\end{aligned} \tag{18}$$

$$\begin{aligned}\pi_{4}&=(p-\omega)Q-c_{e}\\&=(p-\omega)(d-2p+2uv+2\gamma\theta-\gamma\theta\theta_{0}+e\gamma\theta)-\frac{1}{2}ke^{2}\end{aligned} \tag{19}$$

Theorem 2: when $4k-\gamma^{2}\theta^{2}>0$, the profit function of both suppliers and retailers has an optimal solution.

Proof: based on the backward induction, the solution of the Stackelberg equilibrium is solved. Firstly, solve the first derivative of π_{4} with respect to p and e as follows:

$$\frac{\partial\pi_{4}}{\partial p}=d+2\omega-4p+2\gamma\theta+2uv+e\gamma\theta-\gamma\theta_{0}\theta \tag{20}$$

$$\frac{\partial \pi_4}{\partial e} = -ek - \gamma\theta(\omega - p) \tag{21}$$

Then we can get the Hessian matrix of π_4 as: $H_4 = \begin{bmatrix} -4 & \gamma\theta \\ \gamma\theta & -k \end{bmatrix}$. Let M_k be the k-th order major sub-formula of the Hessian matrix, and there are: $M_1 = -4$, $M_2 = 4k - \gamma^2\theta^2$. According to the Hessian matrix negative definite decision theorem, when $4k - \gamma^2\theta^2 > 0$, this Hessian matrix is negative definite. Therefore, π_4 is a joint concave function of p and e, which can be obtained as follows:

$$p^{**} = \frac{dk + 2\omega k + 2\gamma\theta k + 2uvk - \gamma\theta_0\theta k - \gamma^2\omega\theta^2}{4k\text{-}\gamma^2\theta^2} \tag{22}$$

$$e^{**} = \frac{\gamma\theta\left(d - 2\omega + 2\gamma\theta + 2uv - \gamma\theta_0\theta\right)}{4k - \gamma^2\theta^2} \tag{23}$$

Substitute p^{**} and e^{**} into equation (18) to obtain the supplier profit function:

$$\begin{aligned}\pi_3 = &\frac{1}{2\left(4k - \gamma^2\theta^2\right)} z(8Mk + 8kuv^2 - 2M\gamma^2\theta^2 - 4dfk + 8fk\omega \\ &+ 4dkv - 8k\omega v - 8f\gamma k\theta - 8fkuv + 8\gamma k\theta v + 4f\gamma k\theta_0\theta - 4\gamma k\theta_0\theta v) \\ &- \frac{1}{2\left(4k - \gamma^2\theta^2\right)}(8k\omega^2 + 4\delta kv^2 + 4cdk - 8ck\omega - 4dk\omega + 8c\gamma k\theta - 8\gamma k\omega\theta \\ &+ 8ckuv - 8k\omega uv - \delta\gamma^2\theta^2 v^2 - 4c\gamma k\theta_0\theta + 4\gamma k\omega\theta_0\theta)\end{aligned} \tag{24}$$

Accordingly, the Hessian matrix of π_3 can be obtained as: $H_3 = \begin{bmatrix} \frac{8k}{\gamma^2\theta^2 - 4k} & \frac{4k(u-z)}{4k - \gamma^2\theta^2} \\ \frac{4k(u-z)}{4k - \gamma^2\theta^2} & \frac{\delta\gamma^2\theta^2 - 4\delta k + 8kuz}{4k - \gamma^2\theta^2} \end{bmatrix}$.

Let M_k be the k-th order major sub-formula of the Hessian matrix, and there are: $M_1 = \frac{8k}{\gamma^2\theta^2 - 4k}$, $M_2 = \frac{8k\left(\delta\gamma^2\theta^2 - 2ku^2 - 4kuz - 2kz^2 + 4\delta k\right)}{\left(4k - \gamma^2\theta^2\right)^2}$. According to the Hessian matrix negative definite decision theorem, when $\frac{8k}{\gamma^2\theta^2 - 4k} < 0$ and $-\frac{8k\left(\delta\gamma^2\theta^2 + 2ku^2 + 4kuz + 2kz^2 - 4\delta k\right)}{\left(4k - \gamma^2\theta^2\right)^2} > 0$, the Hessian matrix is negative definite.

Therefore, π_3 is a joint concave function of ω and v, which can be obtained as follows:

$$\omega^* = \frac{\left(4dk + 8fku + 8\gamma k\theta - 4\gamma k\theta_0\theta\right)z^2}{\left(8k\right)z^2 + \left(16ku\right)z + 4\delta\gamma^2\theta^2 + 8ku^2 - 16\delta k} \tag{25}$$

$$v^* = \frac{k\left(u+z\right)\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{\delta\gamma^2\theta^2 + 2ku^2 + 4kuz + 2kz^2 - 4\delta k} \tag{26}$$

Substituting ω^* and v^* into equation (22), (23), we can get:

$$p^{**} = \frac{\left(4dk + 8fku + 8\gamma k\theta - 4\gamma k\theta_0\theta\right)z^2}{\left(8k\right)z^2 + \left(16ku\right)z + 4\delta\gamma^2\theta^2 + 8ku^2 - 16\delta k} \tag{27}$$

$$e^{**} = \frac{\delta\gamma\theta\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{2\delta\gamma^2\theta^2 + 4ku^2 + 8kuz + 4kz^2 - 4\delta k} \tag{28}$$

By substituting equation (25), (26), (27), (28) into the demand function and the profit function of suppliers and retailers, the optimal demand and profit function can be obtained:

$$Q_2 = \frac{\delta k\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{\delta\gamma^2\theta^2 + 2ku^2 + 4kuz + 2kz^2 - 2\delta k} \tag{29}$$

$$\pi_3 = \frac{((8Mk)z^3 + (16Mku - 4\delta f^2k)z^2)}{((8k)z^2 + (16ku)z + 4\delta\gamma^2\theta^2 + 8ku^2 - 16\delta k)} \tag{30}$$

$$\pi_4 = \frac{\delta^2 k\left(4k - \gamma^2\theta^2\right)\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)^2}{8\left(\delta\gamma^2\theta^2 + 2ku^2 + 4kuz + 2kz^2 - 2\delta k\right)^2} \tag{31}$$

Lemma 1: under decentralized decision-making, the carbon emission reduction efforts of fresh products cold chain suppliers with carbon constraints, the fresh-keeping efforts of retailers, market demand and total profits of cold chain are higher than those of fresh products cold chain without carbon constraints. Namely：$e^{**} > e^*$, $v^{**} > v^*$, $Q_2 > Q_1$, $\pi^{**} > \pi^*$.

Proof: comparing e^* and e^{**}, v^* and v^{**}, Q_1 and Q_2, $\pi^* = \pi_1 + \pi_2$ and $\pi^{**} = \pi_3 + \pi_4$, there are:

$$\begin{aligned} e^{**} - e^* = & \frac{\delta\gamma\theta\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{2\delta\gamma^2\theta^2 + 4ku^2 + 8kuz + 4kz^2 - 4\delta k} \\ & - \frac{\delta\gamma\theta\left(2c - d - 2\gamma\theta + \gamma\theta_0\theta\right)}{2\left(\delta\gamma^2\theta^2 + 2ku^2 - 4\delta k\right)} > 0 \end{aligned} \tag{32}$$

$$v^{**}-v^{*}=\frac{k(u+z)(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+2ku^2+4kuz+2kz^2-4\delta k}-\frac{ku(2c-d-2\gamma\theta+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+2ku^2-4\delta k}>0 \tag{33}$$

$$Q_2-Q_1=\frac{\delta k(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+2ku^2+4kuz+2kz^2-2\delta k}-\frac{\delta k(2c-d-2\gamma\theta+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+2ku^2-4\delta k}>0 \tag{34}$$

$$\pi^{**}-\pi^{*}=(\pi_3+\pi_4)-(\pi_1+\pi_2)>0 \tag{35}$$

Therefore, $e^{**}>e^{*}$, $v^{**}>v^{*}$, $Q_2>Q_1$, $\pi^{**}>\pi^{*}$ can be proved.

The lemma 1 shows that under decentralized decision-making, compared with no carbon constraint, the cold chain system with carbon constraint can encourage suppliers to improve their carbon emission reduction efforts and retailers' fresh-keeping efforts under the carbon cap-and-trade policy, so that the demand for fresh products will increase, and both suppliers and retailers will obtain higher profits.

4.3. Cold chain decision model of fresh products with carbon constraints under centralized decision-making. In the centralized decision-making environment, suppliers and retailers are regarded as a whole, and their interests are completely consistent. When making centralized decisions in the fresh food cold chain, the optimal retail price, carbon emission reduction effort level and fresh-keeping effort level are determined from the perspective of the overall interests of the fresh food cold chain. Since lemma 1 has proved that the expected return of the cold chain system with carbon constraints is high, this study considers the centralized decision-making with carbon constraints. At this time, the profit of the whole cold chain is expressed as:

$$\begin{aligned}\pi_5&=(p-c)Q+z[M-(f-v)Q]-c_e-c_v\\&=z(M-(f-v)(d-2p+2\gamma\theta+2uv+e\gamma\theta-\gamma\theta\theta_0))-\frac{1}{2}ke^2\\&\quad-(c-p)(d-2p+2\gamma\theta+2uv+e\gamma\theta-\gamma\theta\theta_0)-\frac{1}{2}\delta v^2\end{aligned} \tag{36}$$

Solve the first derivative of π_5 with respect to p, e, v:

$$\frac{\partial\pi_5}{\partial p}=2c+d-4p+2\gamma\theta+2fz+2uv-2vz+e\gamma\theta-\gamma\theta_0\theta \tag{37}$$

$$\frac{\partial \pi_5}{\partial e} = -ek - \gamma\theta(c-p) - \gamma\theta z(f-v) \tag{38}$$

$$\frac{\partial \pi_5}{\partial v} = dz - \delta v - 2cu + 2pu - 2pz - 2fuz + 2\gamma\theta z + 4uvz + e\gamma\theta z - \gamma\theta_0\theta z \tag{39}$$

Theorem 3: when $4k - \gamma^2\theta^2 > 0$ and $8kuz + 4ku^2 + 4k(z^2-1) + 4\gamma^2\theta^2 z(1-z) + \gamma^2\theta^2\delta < 0$, there is an optimal solution in the cold chain of fresh products.

Proof: the Hessian matrix of π_5 is: $H_5 = \begin{bmatrix} -4 & \gamma\theta & 2u-2z \\ \gamma\theta & -k & \gamma\theta z \\ 2u-2z & \gamma\theta z & 4uz-\delta \end{bmatrix}$. Let M_k be the k-th order major sub-formula of the Hessian matrix, and there are: $M_1 = -4$, $M_2 = 4k - \gamma^2\theta^2$, $M_3 = 8kuz + 4ku^2 + 4k(z^2-1) + 4\gamma^2\theta^2 z(1-z) + \gamma^2\theta^2\delta$. According to the Hessian matrix negative definite decision theorem, when $4k - \gamma^2\theta^2 > 0$ and $8kuz + 4ku^2 + 4k(z^2-1) + 4\gamma^2\theta^2 z(1-z) + \gamma^2\theta^2\delta < 0$, the Hessian matrix is negative definite. Therefore, there is an optimal solution in the fresh product cold chain. Let $\frac{\partial \pi_5}{\partial p} = 0$, $\frac{\partial \pi_5}{\partial e} = 0$, $\frac{\partial \pi_5}{\partial v} = 0$, and we can get the optimal response function p^{***}, e^{***}, v^{***}.

$$p^{***} = \frac{\left(2dk + 4fku + 4\gamma k\theta - 2\gamma k\theta_0\theta\right)z^2}{(4k)z^2 + (8ku)z + \delta\gamma^2\theta^2 + 4ku^2 - 4\delta k} \tag{38}$$

$$e^{***} = \frac{\delta\gamma\theta\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{\delta\gamma^2\theta^2 + 4ku^2 + 8kuz + 4kz^2 - 4\delta k} \tag{39}$$

$$v^{***} = \frac{k(u+z)\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{\delta\gamma^2\theta^2 + 2ku^2 + 4kuz + 2kz^2 - 4\delta k} \tag{40}$$

By substituting p^{***}, e^{***}, v^{***} into equation (33), the optimal demand and profit can be obtained:

$$Q_3 = \frac{2\delta k\left(2c - d - 2\gamma\theta + 2fz + \gamma\theta_0\theta\right)}{\delta\gamma^2\theta^2 + 4ku^2 + 8kuz + 4kz^2 - 4\delta k} \tag{41}$$

$$\pi_5=\frac{(8Mk)z^3+\left(16Mku-4\delta f^2k\right)z^2}{(8k)z^2+(16ku)z+2\delta\gamma^2\theta^2+8ku^2-8\delta k}+\frac{\left(8Mku^2-8M\delta k+2M\delta\gamma^2\theta^2+4d\delta fk+8\delta f\gamma k\theta\right)z}{(8k)z^2+(16ku)z+2\delta\gamma^2\theta^2+8ku^2-8\delta k} \tag{42}$$

By comparing theorem 2 and theorem 3, we can get the lemma as follows:

Lemma 2: Under the carbon cap-and-trade policy, the level of carbon emission reduction efforts in the cold chain under centralized decision-making is equal to that under decentralized decision-making, but the level of fresh-keeping efforts, market demand and total profits of the cold chain under centralized decision-making are higher than those under decentralized decision-making. Namely： $v^{**}=v^{***}$, $e^{***}>e^{**}$, $Q_3>Q_2$, $\pi^{***}>\pi^{**}$.

Proof: comparing v^* and v^{**}, e^* and e^{**}, Q_1 and Q_2, $\pi_3+\pi_4=\pi^{**}$ and $\pi_5=\pi^{***}$, there are:

$$v^{**}=v^{***}=\frac{k(u+z)(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+2ku^2+4kuz+2kz^2-4\delta k} \tag{43}$$

$$e^{***}-e^{**}=\frac{\delta\gamma\theta(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+4ku^2+8kuz+4kz^2-4\delta k}-\frac{\delta\gamma\theta(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{2\delta\gamma^2\theta^2+4ku^2+8kuz+4kz^2-4\delta k}>0 \tag{44}$$

$$Q_3-Q_2=\frac{2\delta k(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+4ku^2+8kuz+4kz^2-4\delta k}-\frac{\delta k(2c-d-2\gamma\theta+2fz+\gamma\theta_0\theta)}{\delta\gamma^2\theta^2+2ku^2+4kuz+2kz^2-2\delta k}>0 \tag{45}$$

$$\pi^{***}-\pi^{**}=\pi_5-(\pi_3+\pi_4)>0 \tag{46}$$

Therefore, $v^{**}=v^{***}$, $e^{***}>e^{**}$, $Q_3>Q_2$, $\pi^{***}>\pi^{**}$ can be proved.

The lemma 2 shows that the carbon emission reduction level under centralized decision-making is the same as that under decentralized decision-making, so the carbon emission per unit of fresh products is also the same. However, in the centralized decision-making mode, the level of fresh-keeping efforts, the demand for fresh products and the total profit of the system are higher. The main reason is that under the decentralized decision-making, due to the opaque information of each node of the cold chain, in the operation process of the fresh products cold chain, each node of the supply chain only aims to maximize its own interests and ignores the overall interests, resulting in a “double marginal effect” in the fresh products cold chain.

5. Numerical Analysis and Simulation

Based on the optimal decision-making model of fresh food cold chain under carbon cap-and-trade constraints, this paper evaluates the main parameters and analyzes the examples with the help of MATLAB software. The initial values of relevant parameters are set as follows: $c=1$, $d=15$, $\gamma=6$, $\theta=1$, $\theta_0=0.3$, $\beta=0.6$, $k=2$, $\delta=2$, $u=1$.

5.1. Benefit analysis of fresh products cold chain model under different decision-making modes.

According to the policy documents on carbon cap-and-trade issued by national and local governments and based on the operation of the carbon trading market, make $z=8$, $M=10$, $f=1$. Calculate and analyze the benefits of the fresh products cold chain model under different decision-making modes, and the results are shown in Table 1.

Table 1: Cold chain benefits under different decision-making modes

Decision making mode	Model	π (Profit)	Numerical value
Decentralized decision-making	Carbon free constraint model	π_1	8.9707
		π_2	4.1863
	Carbon cap-and-trade model	π_3	79.9540
		π_4	0.0230
Centralized decision-making	Carbon cap-and-trade model	π_5	83.8676

Through calculation, the profit comparison of different decision-making modes is shown in Table 1. It can be concluded that under the decision-making mode of carbon cap-and-trade policy, the profits of the cold chain system are higher than those without carbon constraints, indicating that the carbon cap-and-trade policy can effectively improve the profits of the cold chain system.

5.2. The impact of carbon trading price on decision-making and benefits of fresh products cold chain.

(1) The impact of carbon trading price on the level of fresh-keeping efforts

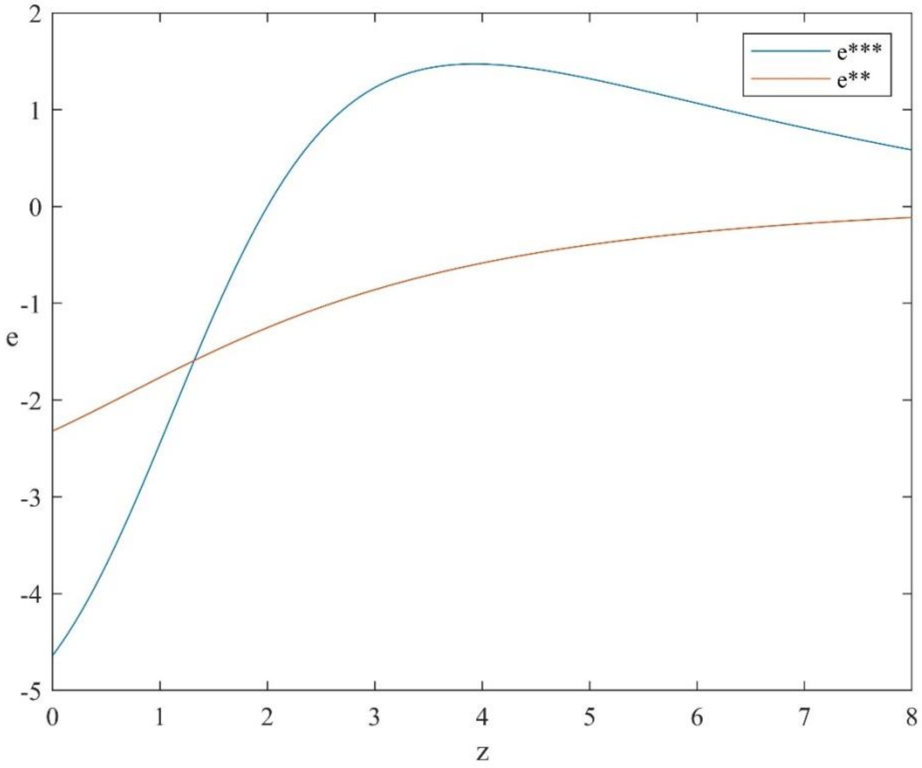

Figure 1: The impact of carbon trading price on the level of fresh-keeping efforts

It can be seen from Figure 1 that with the continuous increase of carbon trading price z, the level of fresh-keeping efforts first increases and then decreases, and the level of fresh-keeping efforts under centralized decision-making is higher than that under decentralized decision-making. This is because with the increase of carbon trading price, the profits obtained by suppliers through carbon trading will gradually increase, and then suppliers will increase their investment in carbon emission reduction and appropriately reduce the level of fresh-keeping efforts.

(2) The impact of carbon trading price on the level of carbon emission reduction efforts

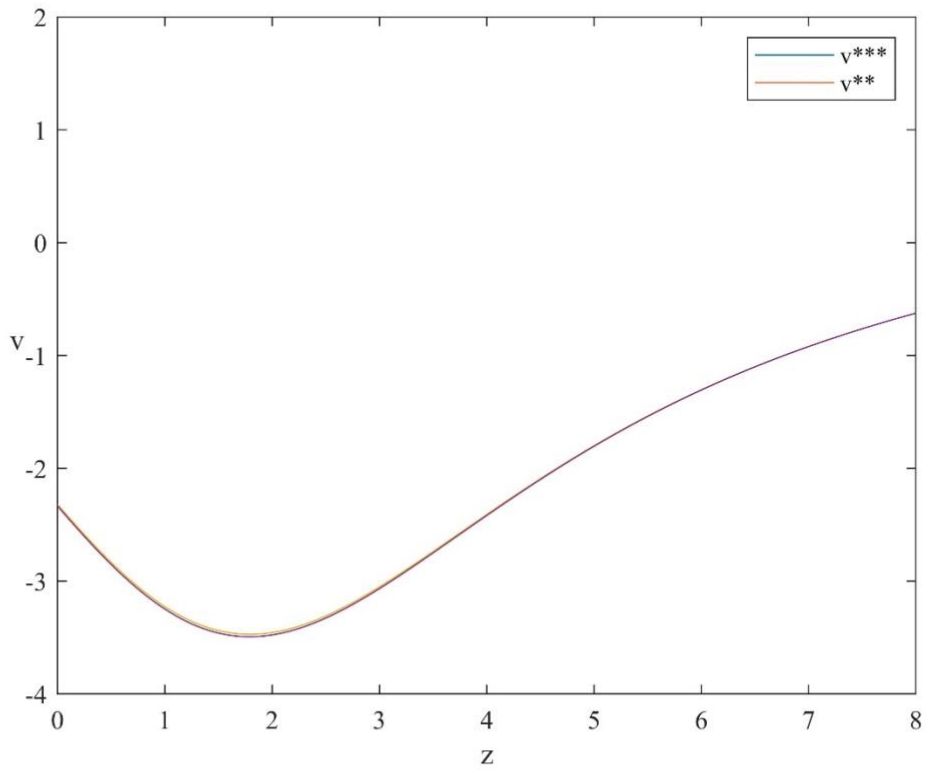

Figure 2: The impact of carbon trading price on the level of carbon emission reduction efforts

The level of carbon emission reduction efforts under decentralized decision-making and centralized decision-making is the same. It can be seen from Figure 2 that with the continuous increase of carbon trading price z, the level of carbon emission reduction first decreases and then increases. This is because with the increase of carbon trading price, suppliers' profits from carbon trading gradually increase, and then gradually improve the level of carbon emission reduction, and sell the remaining carbon emission quotas to increase profits.

(3) The impact of carbon trading price on profits

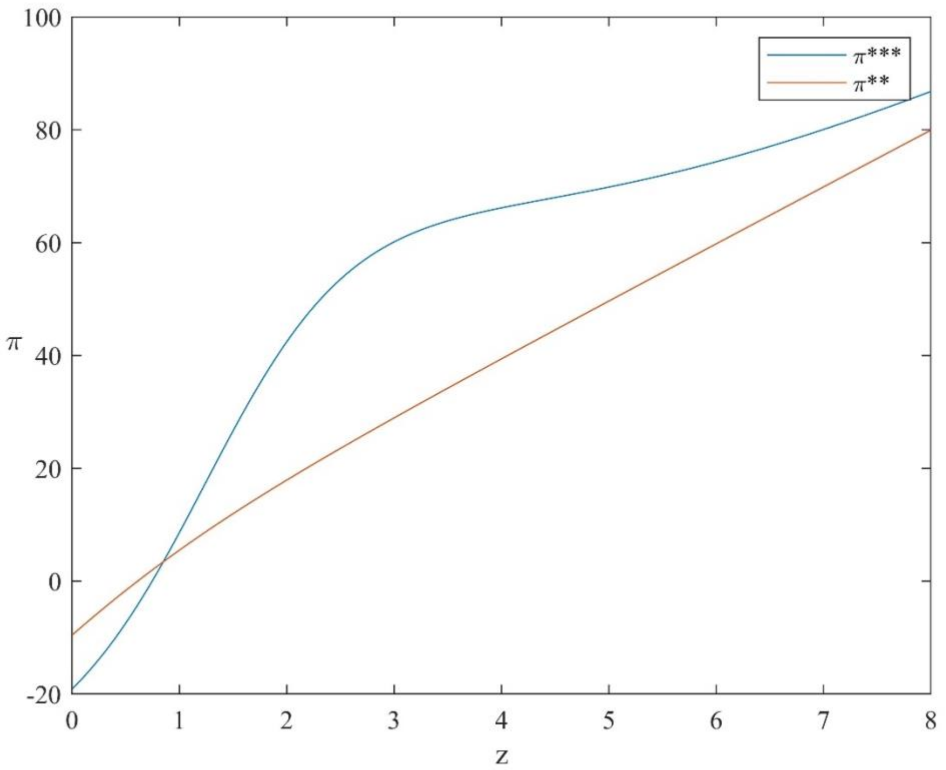

Figure 3: Impact of carbon trading price on profits

It can be seen from Figure 3 that the carbon trading price z is positively correlated with the total profit of the cold chain system. At the same time, the total profit of the cold chain system under centralized decision-making is also significantly higher than that under decentralized decision-making. This shows that the higher the carbon trading price, the more profits suppliers can make from selling excess carbon quotas. Fresh products cold chain suppliers should adjust the decision-making of fresh products cold chain according to the carbon trading price. When the carbon trading price is high, they can improve the system profit by increasing the level of carbon emission reduction efforts. When the price of carbon trading is low and the benefits brought by carbon trading cannot be higher than the costs brought by carbon emission reduction, enterprises should coordinate the relationship between the level of carbon emission reduction efforts and the level of fresh-keeping efforts to improve the sales of fresh products.

5.3. The impact of consumers' low carbon preference and freshness preference on cold chain decision-making and benefits. The experimental results of the impact of carbon trading price on the decision-making and benefits of fresh products cold chain show that the change trend of decision-making variables and economic benefits of the cold chain system under decentralized decision-making and centralized decision-making is basically the same. This section takes the decision-making and benefits of the cold chain system with carbon constraints under decentralized decision-making mode as an example to analyze the impact of consumers' low-carbon preference and freshness preference on system decision-making and benefits.

(1) The impact of consumers' low-carbon preference and freshness preference on the level of fresh-keeping efforts

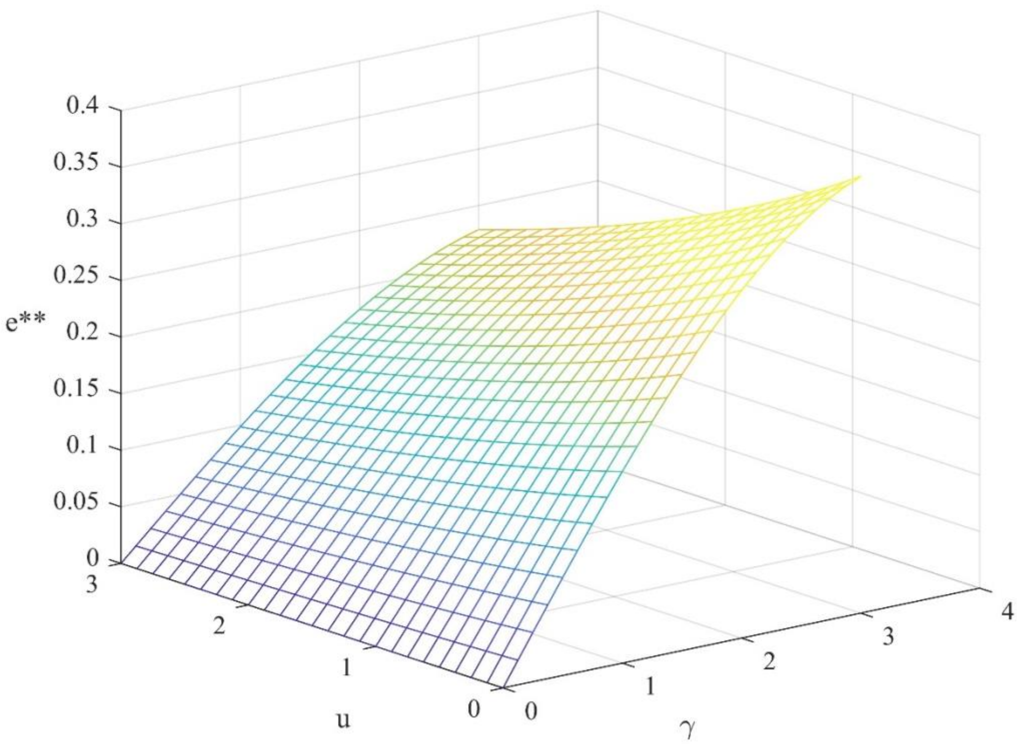

Figure 4: The impact of consumers' low-carbon preference and freshness preference on the level of fresh-keeping efforts

Figure 4 shows that the level of fresh-keeping efforts in the cold chain is mainly affected by γ . with the increase of γ , the level of fresh-keeping efforts will gradually increase. This is because the higher consumers' preference for freshness, the more consumers are willing to buy products with higher freshness, and retailers are more willing to improve the freshness level of fresh agricultural products.

(2) The impact of consumers' low-carbon preference and freshness preference on the level of carbon emission reduction efforts

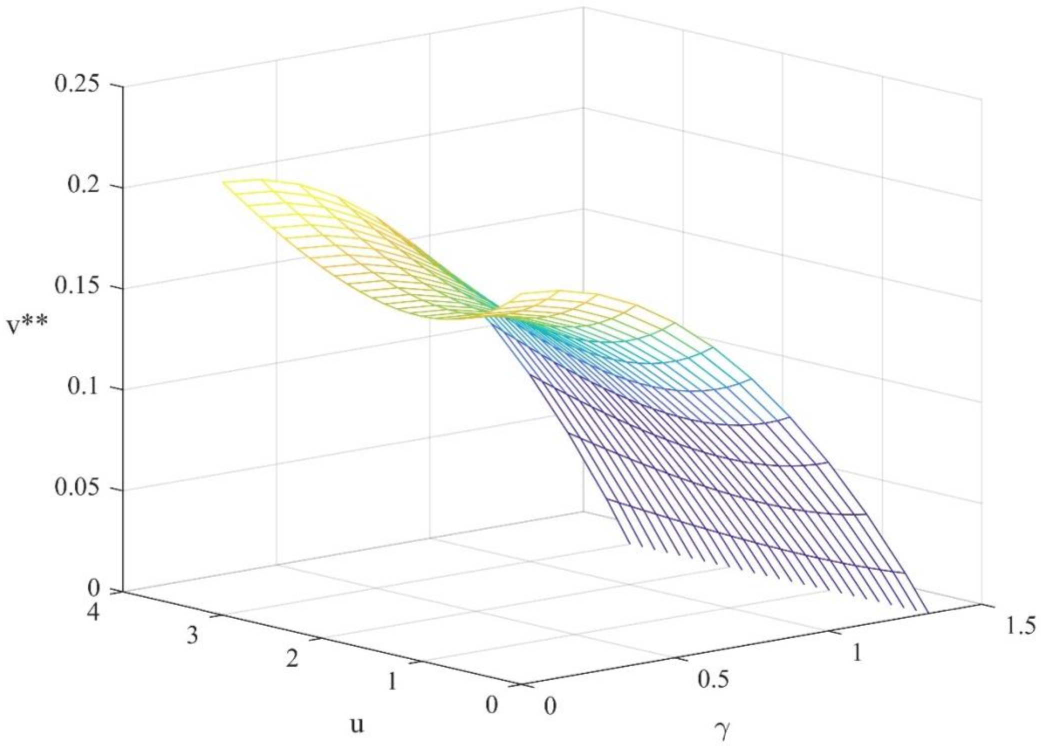

Figure 5: The impact of consumers' low-carbon preference and freshness preference on the level of carbon emission reduction efforts

Figure 5 shows that when γ is in a certain range, the carbon emission reduction level of the cold chain will gradually increase with the increase of u, and when it exceeds this range, the carbon emission reduction level will gradually decrease. This is because when consumers' preference for freshness continues to increase, suppliers will strive to improve the level of fresh-keeping efforts, which will gradually reduce the level of carbon emission reduction efforts and increase the carbon emissions of the cold chain.

(3) The impact of consumers' low carbon preference and freshness preference on profits

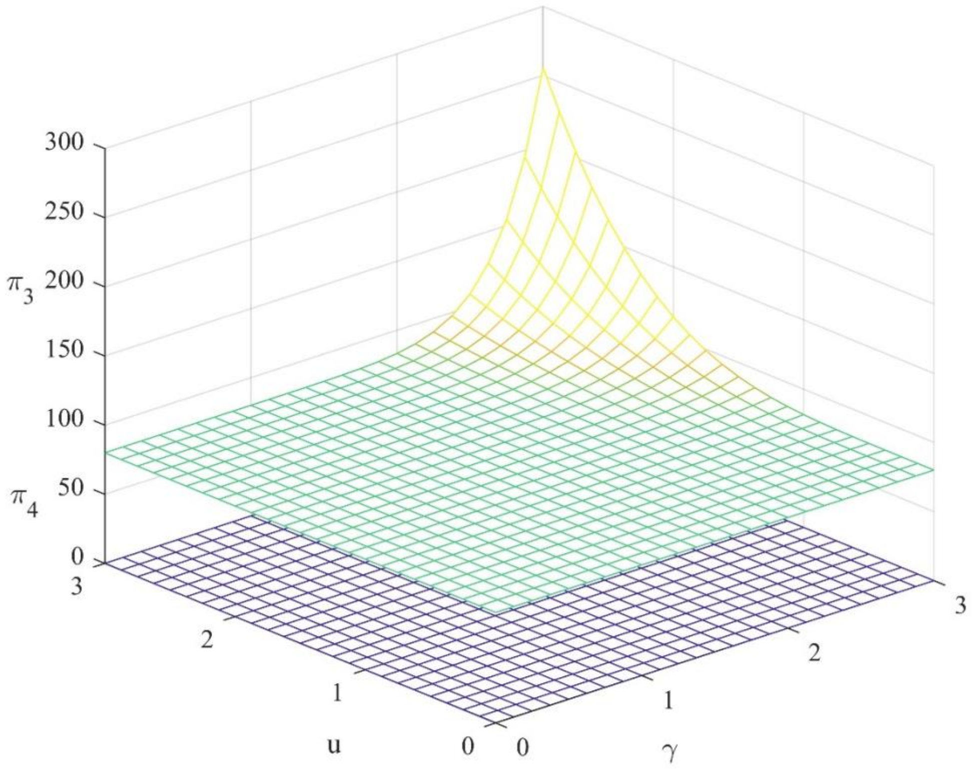

Figure 6: The impact of consumers' low carbon preference and freshness preference on profits

As shown in Figure 6, while consumers' freshness preference and low-carbon preference have increased, the profits of the fresh products cold chain have increased. And the profit of suppliers is always greater than that of retailers. This shows that when consumers are more sensitive to the level of freshness and carbon emission reduction, carbon cap-and-trade policy can more effectively improve the profits of enterprises.

6. Conclusions

By constructing the optimal decision-making model of fresh products cold chain considering retailers' fresh-keeping efforts and suppliers' carbon emission reduction efforts, this paper studies the optimal decision-making of fresh products cold chain without and with carbon constraints under different decision-making modes, and finds the following conclusions:

(1) Fresh keeping efforts have a positive effect on improving the income of fresh products cold chain, but decision makers will ignore the impact of carbon emission reduction on cold chain production.

(2) The profit of the fresh products cold chain system under the carbon cap-and-trade policy is significantly higher than that under the carbon free constraint.

(3) The carbon emission reduction effort level of the carbon free constraint model is lower than that of the carbon cap-and-trade model. Consumer freshness preference, low-carbon preference and the price of carbon trading will also affect the level of carbon emission reduction efforts.

(4) Fresh products cold chain enterprises should actively practice the policy of carbon cap-and-trade and strive to improve the level of freshness keeping efforts and carbon reduction efforts, thereby increasing revenue and promoting the sustainable development of the cold chain system.

(5) The government should step up its efforts in low-carbon publicity and macro-regulate the price of carbon trading and the carbon credits of enterprises, so as to motivate them to increase their efforts in carbon emission reduction and cultivate people's awareness of sustainable development.

This paper studies only a simple decision-making model of the two-level cold chain system under the carbon cap-and-trade policy. In practice, the network structure of the cold chain system will be more complex, and considering that the actual carbon emissions and carbon trading prices will tend to change with the relationship between supply and demand, resulting in an impact on the subsequent sales cycle. Later, based on the more complex cold chain structure and the dynamic carbon emission trading market, we will study the multi cycle cold chain decision-making.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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